INST 231 (PLC Programming), section 2

Lab

PLC-based motor control system: *Question 51 and 52*, **completed objectives due by the end of day 3**

Exam

Day 3 – only a simple calculator may be used!

Specific objectives for the "mastery" exam:

- Electricity Review: Calculate voltages, currents, powers and/or resistances in a DC series-parallel circuit
- Sketch proper wire connections for sourcing or sinking PLC I/O points
- Determine status of PLC discrete output given discrete input states and a simple RLL program listing
- Calculate either the full-load current or the horsepower of an electric motor (either single- or three-phase) given the line voltage and one of the other parameters
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a simple PLC circuit given a wiring diagram, RLL program listing, and reported symptoms
- INST240 Review: Calculate ranges for hydrostatic (DP) level-measuring instruments given physical dimensions and fluid densities
- INST250 Review: Convert between different pressure units (PSI, "W.C., bar, etc.) showing proper mathematical cancellation of units (i.e. the "unity fraction" technique)
- INST262 Review: Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table

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Recommended daily schedule

Day 1

Theory session topic: Timer instructions

Questions 1 through 20; answer questions 1-7 in preparation for discussion (remainder for practice)

Day 2

Theory session topic: Timer applications and Review for exam

Questions 21 through 40; answer questions 21-28 in preparation for discussion (remainder for practice)

Feedback questions *(41 through 50)* are optional and may be submitted for review at the end of the day

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Day 3

Exam

Course Syllabus

INSTRUCTOR CONTACT INFORMATION:

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DEPT/COURSE #: INST 231

CREDITS: 3 **Lecture Hours:** 10 **Lab Hours:** 50 **Work-based Hours:** 0

COURSE TITLE: PLC Programming

COURSE DESCRIPTION: In this course you will learn how to wire, program, and configure programmable logic controllers (PLCs) to perform discrete control functions including combinational logic, counters, and timers. **Pre/Corequisite course:** INST 230 (Motor Controls) **Prerequisite course:** MATH&141 (Precalculus 1) with a minimum grade of "C"

COURSE OUTCOMES: Construct, program, and efficiently diagnose control systems incorporating programmable logic controllers (PLCs).

COURSE OUTCOME ASSESSMENT: PLC wiring, programming, and configuration outcomes are ensured by measuring student performance against mastery standards, as documented in the Student Performance Objectives. Failure to meet all mastery standards by the next scheduled exam day will result in a failing grade for the course.

STUDENT PERFORMANCE OBJECTIVES:

- Without references or notes, within a limited time (3 hours total for each exam session), independently perform the following tasks. Multiple re-tries are allowed on mastery (100% accuracy) objectives, each with a different set of problems:
  → Calculate voltages, currents, powers, and/or resistances in a DC series-parallel circuit, with 100% accuracy (mastery)
  → Sketch proper wire connections for sourcing or sinking PLC I/O points given schematic or pictorial diagrams of the components, with 100% accuracy (mastery)
  → Determine status of a PLC discrete output given input states and a simple RLL program, with 100% accuracy (mastery)
  → Calculate either the full-load current or the horsepower of an electric motor (either single- or three-phase) given the line voltage and one of the other parameters
  → Solve for specified variables in algebraic formulae, with 100% accuracy (mastery)
  → Determine the possibility of suggested faults in a simple PLC circuit given measured values (voltage, current), a schematic diagram, and reported symptoms, with 100% accuracy (mastery)
  → Program a PLC to fulfill a specified control system function
- In a team environment and with full access to references, notes, and instructor assistance, perform the following tasks:
  → Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems
  → Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork
  → Construct and commission a motor start/stop system using a PLC as the control element
  → Generate an accurate wiring diagram compliant with industry standards documenting your team's motor control system
- Independently perform the following tasks with 100% accuracy (mastery). Multiple re-tries are allowed with different specifications/conditions each time:
  → Program a start/stop function in a PLC and wire it to control an electromechanical relay

COURSE OUTLINE: A course calendar in electronic format (Excel spreadsheet) resides on the Y: network drive, and also in printed paper format in classroom DMC130, for convenient student access. This calendar is updated to reflect schedule changes resulting from employer recruiting visits, interviews, and other impromptu events. Course worksheets provide comprehensive lists of all course assignments and activities, with the first page outlining the schedule and sequencing of topics and assignment due dates. These worksheets are available in PDF format at `http://www.ibiblio.org/kuphaldt/socratic/sinst`

- INST231 Section 1 (PLC contact, coil, and counter programming): 4 days theory and labwork
- INST231 Section 2 (PLC timer and sequence programming): 2 days theory and labwork + 1 day for mastery/proportional Exams

METHODS OF INSTRUCTION: Course structure and methods are intentionally designed to develop critical-thinking and life-long learning abilities, continually placing the student in an active rather than a passive role.

- **Independent study:** daily worksheet questions specify *reading assignments*, *problems* to solve, and *experiments* to perform in preparation (before) classroom theory sessions. Open-note quizzes and work inspections ensure accountability for this essential preparatory work. The purpose of this is to convey information and basic concepts, so valuable class time isn't wasted transmitting bare facts, and also to foster the independent research ability necessary for self-directed learning in your career.
- **Classroom sessions:** a combination of *Socratic discussion*, short *lectures*, *small-group* problem-solving, and hands-on *demonstrations/experiments* review and illuminate concepts covered in the preparatory questions. The purpose of this is to develop problem-solving skills, strengthen conceptual understanding, and practice both quantitative and qualitative analysis techniques.
- **Hands-on PLC programming challenges:** daily worksheet questions specify realistic scenarios requiring students to develop real PLC programs on their PLC trainers to implement the desired control function(s).
- **Lab activities:** an emphasis on constructing and documenting *working projects* (real instrumentation and control systems) to illuminate theoretical knowledge with practical contexts. Special projects off-campus or in different areas of campus (e.g. BTC's Fish Hatchery) are encouraged. Hands-on *troubleshooting exercises* build diagnostic skills.
- **Feedback questions:** sets of *practice problems* at the end of each course section challenge your knowledge and problem-solving ability in current as as well as first year (Electronics) subjects. These are optional assignments, counting neither for nor against your grade. Their purpose is to provide you and your instructor with direct feedback on what you have learned.

STUDENT ASSIGNMENTS/REQUIREMENTS: All assignments for this course are thoroughly documented in the following course worksheets located at:
`http://www.ibiblio.org/kuphaldt/socratic/sinst/index.html`

- `INST231_sec1.pdf`
- `INST231_sec2.pdf`

EVALUATION AND GRADING STANDARDS: (out of 100% for the course grade)

- Completion of all mastery objectives = 50%
- Mastery exam score (first attempt) = 10%
- Proportional exam score = 30%
- Lab questions = 10%
- Quiz penalty = -1% per failed quiz
- Tardiness penalty = -1% per incident (1 "free" tardy per course)
- Attendance penalty = -1% per hour (12 hours "sick time" per quarter)
- Extra credit = +5% per project (assigned by instructor based on individual learning needs)

All grades are criterion-referenced (i.e. no grading on a "curve")

100% $\geq$ **A** $\geq$ 95%	95% > **A-** $\geq$ 90%		
90% > **B+** $\geq$ 86%	86% > **B** $\geq$ 83%	83% > **B-** $\geq$ 80%	
80% > **C+** $\geq$ 76%	76% > **C** $\geq$ 73%	73% > **C-** $\geq$ 70%	(minimum passing course grade)
70% > **D+** $\geq$ 66%	66% > **D** $\geq$ 63%	63% > **D-** $\geq$ 60%	60% > **F**

A graded "preparatory" quiz at the start of each classroom session gauges your independent learning prior to the session. A graded "summary" quiz at the conclusion of each classroom session gauges your comprehension of important concepts covered during that session. If absent during part or all of a classroom session, you may receive credit by passing comparable quizzes afterward or by having your preparatory work (reading outlines, work done answering questions) thoroughly reviewed prior to the absence.

Absence on a scheduled exam day will result in a 0% score for the proportional exam unless you provide documented evidence of an unavoidable emergency.

If you fail a mastery exam, you must re-take a different version of that mastery exam on a different day. Multiple re-tries are allowed, on a different version of the exam each re-try. There is no penalty levied on your course grade for re-taking mastery exams, but failure to successfully pass a mastery exam by the due date (i.e. by the date of the *next* exam in the course sequence) will result in a failing grade (F) for the course.

If any other "mastery" objectives are not completed by their specified deadlines, your overall grade for the course will be capped at 70% (C- grade), and you will have one more school day to complete the unfinished objectives. Failure to complete those mastery objectives by the end of that extra day (except in the case of documented, unavoidable emergencies) will result in a failing grade (F) for the course.

"Lab questions" are assessed by individual questioning, at any date after the respective lab objective (mastery) has been completed by your team. These questions serve to guide your completion of each lab exercise and confirm participation of each individual student. Grading is as follows: full credit for thorough, correct answers; half credit for partially correct answers; and zero credit for major conceptual errors. All lab questions must be answered by the due date of the lab exercise.

Extra credit opportunities exist for each course, and may be assigned to students upon request. The student and the instructor will first review the student's performance on feedback questions, homework, exams, and any other relevant indicators in order to identify areas of conceptual or practical weakness. Then, both will work together to select an appropriate extra credit activity focusing on those identified weaknesses, for the purpose of strengthening the student's competence. A due date will be assigned (typically two weeks following the request), which must be honored in order for any credit to be earned from the activity. Extra credit may be denied at the instructor's discretion if the student has not invested the necessary preparatory effort to perform well (e.g. lack of preparation for daily class sessions, poor attendance, no feedback questions submitted, etc.).

REQUIRED STUDENT SUPPLIES AND MATERIALS:

- Course worksheets available for download in PDF format
- *Lessons in Industrial Instrumentation* textbook, available for download in PDF format
  → Access worksheets and book at: `http://www.ibiblio.org/kuphaldt/socratic/sinst`
- Spiral-bound notebook for reading annotation, homework documentation, and note-taking.
- Instrumentation reference CD-ROM (free, from instructor). This disk contains many tutorials and datasheets in PDF format to supplement your textbook(s).
- Tool kit (see detailed list)
- Simple scientific calculator (non-programmable, non-graphing, no unit conversions, no numeration system conversions), TI-30Xa or TI-30XIIS recommended
- Small "brick" PLC and HMI panel (*Automation Direct option*):
  → Automation Direct CLICK PLC model C0-00DD1-D (price ≈ $70) 8 discrete (DC) inputs, 6 discrete (DC) outputs
  → *or* Automation Direct CLICK PLC model C0-02DD1-D (price ≈ $130) 4 discrete (DC) inputs, 4 discrete (DC) outputs, 2 analog inputs, 2 analog outputs, RS-485 Modbus communications port, real-time clock and calendar
  → Automation Direct CLICK 24 VDC power supply model C0-00AC (price ≈ $30) 24 VDC at 0.5 amp maximum output
  → Automation Direct C-More Micro HMI panel 3 inch EA1-S3ML-N (price ≈ $150)
  → *optional* Automation Direct C-More Micro touch-screen HMI panel 3 inch EA1-S3ML (price ≈ $190)
  → Automation Direct USB/serial adapter and cable part EA-MG-PGM-CBL (price ≈ $40) necessary for programming the C-More Micro HMI panel (also works for programming the PLC)
  → **Note:** We have found the Autmoation Direct software works equally well through a 9-pin serial port as through a USB port (with converter), and is very "friendly" to use.
- Small "brick" PLC and HMI panel (*Allen-Bradley option*):
  → Rockwell (Allen-Bradley) MicroLogix 1000 model 1761-L10BWA (price ≈ $85 with BTC student discount at North Coast Electric) 6 discrete (DC) inputs, 4 discrete (relay) outputs
  → *or* Rockwell (Allen-Bradley) MicroLogix 1100 model 1763-L16BWA (price ≈ $240 with BTC student discount at North Coast Electric) 10 discrete (DC) inputs, 6 discrete (DC) outputs, 2 analog inputs, RS-485 communication port, 10 Mbit/s Ethernet communication port, embedded web server for remote monitoring of data points (series A or B programmable using free MicroLogix Lite software)
  → Rockwell (Allen-Bradley) cable part 1761-CBL-PM02 (price ≈ $30 with BTC student discount at North Coast Electric)
  → Automation Direct C-More Micro HMI panel 3 inch EA1-S3ML-N (price ≈ $150)
  → *optional* Automation Direct C-More Micro touch-screen HMI panel 3 inch EA1-S3ML (price ≈ $190)
  → Automation Direct cable part EA-MLOGIX-CBL (price ≈ $30) and adapter part EA-MG-SP1 (price ≈ $50) necessary for connecting the C-More Micro HMI panel to an Allen-Bradley MicroLogix 1000 PLC
  → Automation Direct USB/serial adapter and cable part EA-MG-PGM-CBL (price ≈ $40) necessary for programming the C-More Micro HMI panel
  → **Note:** Programming Allen-Bradley PLCs is best done using a PC with a 9-pin serial port. We have found trying to use a USB-to-serial adapter very troublesome with Allen-Bradley software!

ADDITIONAL INSTRUCTIONAL RESOURCES:

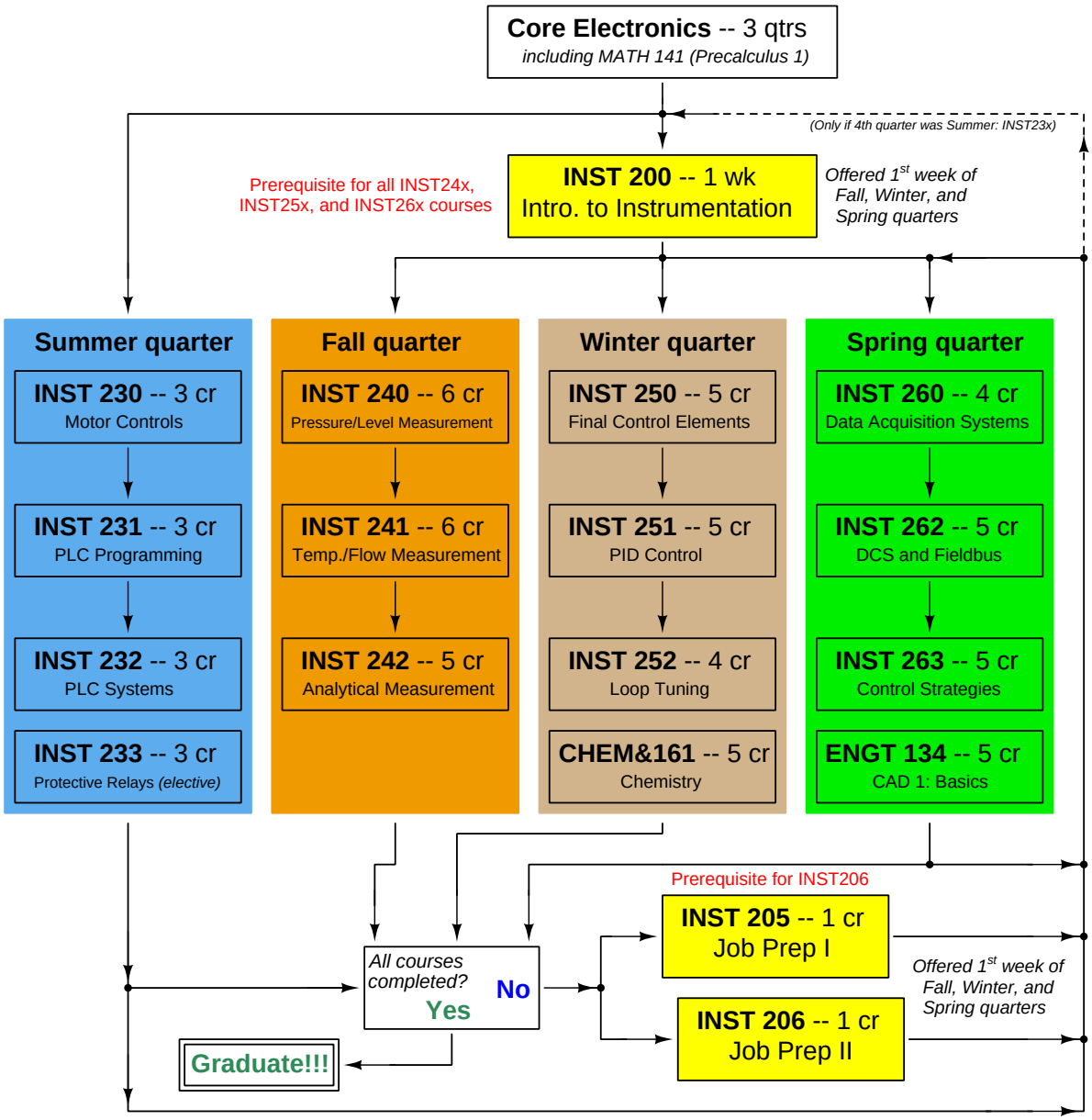
- The BTC Library hosts a substantial collection of textbooks and references on the subject of Instrumentation, as well as links in its online catalog to free Instrumentation e-book resources available on the Internet.
- "BTCInstrumentation" channel on YouTube (`http://www.youtube.com/BTCInstrumentation`), hosts a variety of short video tutorials and demonstrations on instrumentation.
- ISA Student Section at BTC meets regularly to set up industry tours, raise funds for scholarships, and serve as a general resource for Instrumentation students. Membership in the ISA is $10 per year, payable to the national ISA organization. Membership includes a complementary subscription to *InTech* magazine.
- ISA website (`http://www.isa.org`) provides all of its standards in electronic format, many of which are freely available to ISA members.
- *Cad Standard* (CadStd) or similar AutoCAD-like drafting software (useful for sketching loop and wiring diagrams). Cad Standard is a simplified clone of AutoCAD, and is freely available at: `http://www.cadstd.com`

CAMPUS EMERGENCIES: If an emergency arises, your instructor may inform you of actions to follow. You are responsible for knowing emergency evacuation routes from your classroom. If police or university officials order you to evacuate, do so calmly and assist those needing help. You may receive emergency information alerts via the building enunciation system, text message, email, or BTC's webpage (`http://www.btc.ctc.edu`), Facebook or Twitter. Refer to the emergency flipchart in the lab room (located on the main control panel) for more information on specific types of emergencies.

ACCOMMODATIONS: If you think you could benefit from classroom accommodations for a disability (physical, mental, emotional, or learning), please contact our Accessibility Resources office. Call (360)-752-8345, email `ar@btc.ctc.edu`, or stop by the AR Office in the Admissions and Student Resource Center (ASRC), Room 106, College Services Building

file `INST231syllabus`

Sequence of second-year Instrumentation courses



The particular sequence of courses you take during the second year depends on when you complete all first-year courses and enter the second year. Since students enter the second year of Instrumentation at four different times (beginnings of Summer, Fall, Winter, and Spring quarters), the particular course sequence for any student will likely be different from the course sequence of classmates.

Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students, depending on when they first enter the second year of the program:

Possible course schedules depending on date of entry into 2nd year

file sequence

General Values and Expectations

Success in this career requires: professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. Poor judgment spells disaster in this career, which is why employer background checks (including social media and criminal records) and drug testing are common. The good news is that character and clear thinking are malleable traits: unlike intelligence, these qualities can be acquired and improved with effort. *This is what you are in school to do* – increase your "human capital" which is the sum of all knowledge, skills, and traits valuable in the marketplace.

Mastery: You must master the fundamentals of your chosen profession. "Mastery" assessments challenge you to demonstrate 100% competence (with multiple opportunities to re-try). Failure to complete any mastery objective(s) by the deadline date caps your grade at a C−. Failure to complete by the end of the next school day results in a failing (F) grade.

Punctuality and Attendance: You are expected to arrive on time and be "on-task" all day just as you would for a job. Each student has 12 hours of "sick time" per quarter applicable to absences not verifiably employment-related, school-related, weather-related, or required by law. Each student must confer with the instructor to apply these hours to any missed time – this is not done automatically. Students may donate unused "sick time" to whomever they specifically choose. You must contact your instructor and lab team members immediately if you know you will be late or absent or must leave early. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

Time Management: You are expected to budget and prioritize your time, just as you will be on the job. You will need to reserve enough time outside of school to complete homework, and strategically apply your time during school hours toward limited resources (e.g. lab equipment). Frivolous activities (e.g. games, social networking, internet surfing) are unacceptable when work is unfinished. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

Independent Study: This career is marked by continuous technological development and ongoing change, which is why *self-directed learning* is ultimately more important to your future success than specific knowledge. To acquire and hone this skill, all second-year Instrumentation courses follow an "inverted" model where lecture is replaced by independent study, and class time is devoted to addressing your questions and demonstrating your learning. Most students require a *minimum* of 3 hours daily study time outside of school. Arriving unprepared (e.g. homework incomplete) is unprofessional and counter-productive. Question 0 of every worksheet lists practical study tips.

Independent Problem-Solving: The best instrument technicians are versatile problem-solvers. General problem-solving is arguably the most valuable skill you can possess for this career, and it can only be built through persistent effort. This is why you must take every reasonable measure to *solve problems on your own* before seeking help. It is okay to be perplexed by an assignment, but you are expected to apply problem-solving strategies given to you (see Question 0) and to precisely identify where you are confused so your instructor will be able to offer targeted help. Asking classmates to solve problems for you is folly – this includes having others break the problem down into simple steps. The point is to learn how to *think on your own*. When troubleshooting systems in lab you are expected to run diagnostic tests (e.g. using a multimeter instead of visually seeking circuit faults), as well as consult the equipment manual(s) before seeking help.

Initiative: No single habit predicts your success or failure in this career better than personal initiative, which is why your instructor will demand *you do for yourself rather than rely on others to do for you.* Examples include setting up and using your BTC email account to communicate with your instructor(s), consulting manuals for technical information before asking for help, regularly checking the course calendar and assignment deadlines, avoiding procrastination, fixing small problems before they become larger problems, etc. If you find your performance compromised by poor understanding of prior course subjects, re-read those textbook sections and use the practice materials made available to you on the Socratic Instrumentation website – don't wait for anyone else to diagnose your need and offer help.

Safety: You are expected to work safely in the lab just as you will be on the job. This includes wearing proper attire (safety glasses and closed-toed shoes in the lab at all times), implementing lock-out/tag-out procedures when working on circuits with exposed conductors over 30 volts, using ladders to access elevated locations, and correctly using all tools. If you need to use an unfamiliar tool, see the instructor for directions.

Orderliness: You are expected to keep your work area clean and orderly just as you will be on the job. This includes discarding trash and returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. If you identify failed equipment in the lab, label that equipment with a detailed description of its symptoms.

Teamwork: You will work in instructor-assigned teams to complete lab assignments, just as you will work in teams to complete complex assignments on the job. As part of a team, you must keep your teammates informed of your whereabouts in the event you must step away from the lab or will be absent for *any* reason. Any student regularly compromising team performance through lack of participation, absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually for the remainder of the quarter. The same is true for students found relying on teammates to do their work for them.

Cooperation: The structure of these courses naturally lends itself to cooperation between students. Working together, students significantly impact each others' learning. You are expected to take this role seriously, offering real help when needed and not absolving classmates of their responsibility to think for themselves or to do their own work. Solving problems for classmates and/or explaining to them what they can easily read on their own is unacceptable because these actions circumvent learning. The best form of help you can give to your struggling classmates is to share with them your tips on independent learning and problem-solving, for example *asking questions* leading to solutions rather than simply providing solutions for them.

Grades: Employers prize trustworthy, hard working, knowledgeable, resourceful problem-solvers. The grade you receive in any course is but a *partial* measure of these traits. What matters most are the traits themselves, which is why your instructor maintains detailed student records (including individual exam scores, attendance, tardiness, and behavioral comments) and will share these records with employers if you have signed the FERPA release form. You are welcome to see your records at any time, and to compare calculated grades with your own records (i.e. the grade spreadsheet available to all students). You should expect employers to scrutinize your records on attendance and character, and also challenge you with technical questions when considering you for employment.

Representation: You are an ambassador for this program. Your actions, whether on tours, during a jobshadow or internship, or while employed, can open or shut doors of opportunity for other students. Most of the job opportunities open to you as a BTC graduate were earned by the good work of previous graduates, and as such you owe them a debt of gratitude. Future graduates depend on you to do the same.

Responsibility For Actions: If you lose or damage college property (e.g. lab equipment), you must find, repair, or help replace it. If you represent BTC poorly to employers (e.g. during a tour or an internship), you must make amends. The general rule here is this: *"If you break it, you fix it!"*

Non-negotiable terms: disciplinary action, up to and including immediate failure of a course, will result from academic dishonesty (e.g. cheating, plagiarism), willful safety violations, theft, harassment, intoxication, destruction of property, or willful disruption of the learning (work) environment. Such offenses are grounds for immediate termination in this career, and as such will not be tolerated here.

file `expectations`

General tool and supply list

Wrenches

- Combination (box- and open-end) wrench set, 1/4" to 3/4" – *the most important wrench sizes are 7/16", 1/2", 9/16", and 5/8"; get these immediately!*
- Adjustable wrench, 6" handle (sometimes called "Crescent" wrench)
- Hex wrench ("Allen" wrench) set, fractional – 1/16" to 3/8"
- *Optional:* Hex wrench ("Allen" wrench) set, metric – 1.5 mm to 10 mm
- *Optional:* Miniature combination wrench set, 3/32" to 1/4" (sometimes called an "ignition wrench" set)

Note: *when turning any threaded fastener, one should choose a tool engaging the maximum amount of surface area on the fastener's head in order to reduce stress on that fastener. (e.g. Using box-end wrenches instead of adjustable wrenches; using the proper size and type of screwdriver; never using any tool that mars the fastener such as pliers or vise-grips unless absolutely necessary.)*

Pliers

- Needle-nose pliers
- Tongue-and-groove pliers (sometimes called "Channel-lock" pliers)
- Diagonal wire cutters (sometimes called "dikes")

Screwdrivers

- Slotted, 1/8" and 1/4" shaft
- Phillips, #1 and #2
- Jeweler's screwdriver set
- *Optional:* Magnetic multi-bit screwdriver (e.g. Klein Tools model 70035)

Electrical

- Multimeter, Fluke model 87-IV or better
- Alligator-clip jumper wires
- Soldering iron (10 to 40 watt) and rosin-core solder
- Resistor, potentiometer, diode assortments (from first-year lab kits)
- Package of insulated compression-style fork terminals (14 to 18 AWG wire size, #10 stud size)
- Wire strippers/terminal crimpers for 10 AWG to 18 AWG wire and insulated terminals
- *Optional:* ratcheting terminal crimp tool (e.g. Paladin 1305, Ferrules Direct FDT10011, or equivalent)

Safety

- Safety glasses or goggles (available at BTC bookstore)
- Earplugs (available at BTC bookstore)

Miscellaneous

- Simple scientific calculator (non-programmable, non-graphing, no conversions), TI-30Xa or TI-30XIIS recommended. Required for some exams!
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

An inexpensive source of tools is your local pawn shop. Look for tools with unlimited lifetime guarantees (e.g. *Sears* "Craftsman" brand). Check for BTC student discounts as well!

file `tools`

Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*.

Theory

In the theory portion of each course, students independently research subjects *prior* to entering the classroom for discussion. This means working through all the day's assigned questions as completely as possible. This usually requires a fair amount of technical reading, and may also require setting up and running simple experiments. At the start of the classroom session, the instructor will check each student's preparation with a quiz. Students then spend the rest of the classroom time working in groups and directly with the instructor to *thoroughly* answer all questions assigned for that day, articulate problem-solving strategies, and to approach the questions from multiple perspectives. To put it simply: fact-gathering happens outside of class and is the individual responsibility of each student, so that class time may be devoted to the more complex tasks of critical thinking and problem solving where the instructor's attention is best applied.

Classroom theory sessions usually begin with either a brief Q&A discussion or with a "Virtual Troubleshooting" session where the instructor shows one of the day's diagnostic question diagrams while students propose diagnostic tests and the instructor tells those students what the test results would be given some imagined ("virtual") fault scenario, writing the test results on the board where all can see. The students then attempt to identify the nature and location of the fault, based on the test results.

Each student is free to leave the classroom when they have completely worked through all problems and have answered a "summary" quiz designed to gauge their learning during the theory session. If a student finishes ahead of time, they are free to leave, or may help tutor classmates who need extra help.

The express goal of this "inverted classroom" teaching methodology is to help each student cultivate critical-thinking and problem-solving skills, and to sharpen their abilities as independent learners. While this approach may be very new to you, it is more realistic and beneficial to the type of work done in instrumentation, where critical thinking, problem-solving, and independent learning are "must-have" skills.

Lab

In the lab portion of each course, students work in teams to install, configure, document, calibrate, and troubleshoot working instrument loop systems. Each lab exercise focuses on a different type of instrument, with a eight-day period typically allotted for completion. An ordinary lab session might look like this:

(1) Start of practical (lab) session: announcements and planning
   (a) The instructor makes general announcements to all students
   (b) The instructor works with team to plan that day's goals, making sure each team member has a clear idea of what they should accomplish
(2) Teams work on lab unit completion according to recommended schedule:
   (First day) Select and bench-test instrument(s)
   (One day) Connect instrument(s) into a complete loop
   (One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
   (One or two days) Each team member calibrates/configures the instrument(s)
   (Remaining days, up to last) Each team member troubleshoots the instrument loop
(3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

Troubleshooting assessments must meet the following guidelines:

- Troubleshooting must be performed *on a system the student did not build themselves.* This forces students to rely on another team's documentation rather than their own memory of how the system was built.
- Each student must individually demonstrate proper troubleshooting technique.
- Simply finding the fault is not good enough. Each student must consistently demonstrate sound reasoning while troubleshooting.
- If a student fails to properly diagnose the system fault, they must attempt (as many times as necessary) with different scenarios until they do, reviewing any mistakes with the instructor after each failed attempt.

file `instructional`

Distance delivery methods

Sometimes the demands of life prevent students from attending college 6 hours per day. In such cases, there exist alternatives to the normal 8:00 AM to 3:00 PM class/lab schedule, allowing students to complete coursework in non-traditional ways, at a "distance" from the college campus proper.

For such "distance" students, the same worksheets, lab activities, exams, and academic standards still apply. Instead of working in small groups and in teams to complete theory and lab sections, though, students participating in an alternative fashion must do all the work themselves. Participation via teleconferencing, video- or audio-recorded small-group sessions, and such is encouraged and supported.

There is no recording of hours attended or tardiness for students participating in this manner. The pace of the course is likewise determined by the "distance" student. Experience has shown that it is a benefit for "distance" students to maintain the same pace as their on-campus classmates whenever possible.

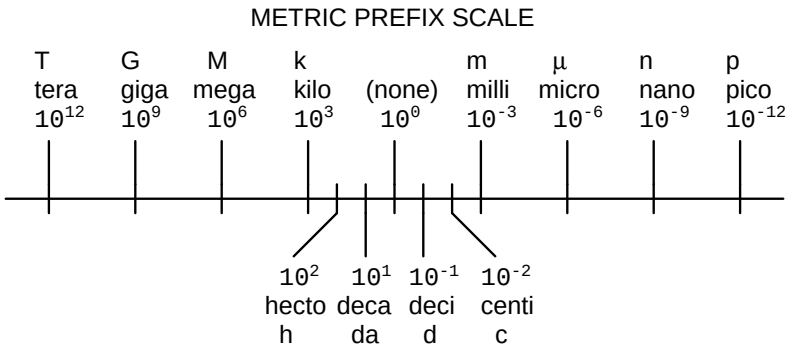
In lieu of small-group activities and class discussions, comprehension of the theory portion of each course will be ensured by completing and submitting detailed answers for *all* worksheet questions, not just passing daily quizzes as is the standard for conventional students. The instructor will discuss any incomplete and/or incorrect worksheet answers with the student, and ask that those questions be re-answered by the student to correct any misunderstandings before moving on.

Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either by arranging time in the school lab facility and/or completing activities on equivalent equipment outside of school (e.g. at their place of employment, if applicable). Labwork completed outside of school must be validated by a supervisor and/or documented via photograph or videorecording.

Conventional students may opt to switch to "distance" mode at any time. This has proven to be a benefit to students whose lives are disrupted by catastrophic events. Likewise, "distance" students may switch back to conventional mode if and when their schedules permit. Although the existence of alternative modes of student participation is a great benefit for students with challenging schedules, it requires a greater investment of time and a greater level of self-discipline than the traditional mode where the student attends school for 6 hours every day. No student should consider the "distance" mode of learning a way to have more free time to themselves, because they will actually spend more time engaged in the coursework than if they attend school on a regular schedule. It exists merely for the sake of those who cannot attend during regular school hours, as an alternative to course withdrawal.

file `distance`

- **Metric prefixes**
- Yotta = 10^{24} Symbol: Y
- Zeta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^{9} Symbol: G
- Mega = 10^{6} Symbol: M
- Kilo = 10^{3} Symbol: k
- Hecto = 10^{2} Symbol: h
- Deca = 10^{1} Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: μ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y



- **Conversion formulae for temperature**
- ^{o}F = (^{o}C)(9/5) + 32
- ^{o}C = (^{o}F - 32)(5/9)
- ^{o}R = ^{o}F + 459.67
- K = ^{o}C + 273.15

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm^3)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – "International Table") = 251.996 calories (cal – "International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Physical constants

Speed of light in a vacuum (c) = 2.9979×10^8 meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number (N_A) = 6.022×10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602×10^{-19} Coulomb (C)

Boltzmann's constant (k) = 1.38×10^{-23} Joules per Kelvin (J/K)

Stefan-Boltzmann constant (σ) = 5.67×10^{-8} Watts per square meter-Kelvin^4 ($W/m^2 \cdot K^4$)

Molar gas constant (R) = 8.314 Joules per mole-Kelvin (J/mol-K)

Properties of Water

Freezing point at sea level = $32^oF = 0^oC$

Boiling point at sea level = $212^oF = 100^oC$

Density of water at 4^oC = 1000 kg/m^3 = 1 g/cm^3 = 1 kg/liter = 62.428 lb/ft^3 = 1.94 $slugs/ft^3$

Specific heat of water at 14^oC = 1.00002 calories/g·^oC = 1 BTU/lb·^oF = 4.1869 Joules/g·^oC

Specific heat of ice $\approx$ 0.5 calories/g·^oC

Specific heat of steam $\approx$ 0.48 calories/g·^oC

Absolute viscosity of water at 20^oC = 1.0019 centipoise (cp) = 0.0010019 Pascal-seconds (Pa·s)

Surface tension of water (in contact with air) at 18^oC = 73.05 dynes/cm

pH of pure water at 25^o C = 7.0 (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20^oC and 760 torr = 1.204 mg/cm^3 = 1.204 kg/m^3 = 0.075 lb/ft^3 = 0.00235 $slugs/ft^3$

Absolute viscosity of dry air at 20^oC and 760 torr = 0.018 centipoise (cp) = 1.8×10^{-5} Pascal-seconds (Pa·s)

file `conversion_constants`

Question 0

How to get the most out of academic reading:

- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Write your thoughts as you read, noting points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications. These notes should also document important math formulae, explaining in your own words what each formula means and the proper units of measurement used.
- Outline, don't highlight! Writing your own summary or outline is a far more effective way to comprehend a text than simply underlining and highlighting key words. A suggested ratio is one sentence of your own thoughts per paragraph of text read. Note points of disagreement or confusion to explore later.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Write your own questions based on what you read, as though you are a teacher preparing to test students' comprehension of the subject matter.

How to effectively problem-solve and troubleshoot:

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work. In mathematical problem-solving this means being able to identify the practical meaning (and units of measurement) of every intermediate calculation. In other words, *every step of your solution should make logical sense.*
- Sketch a diagram to help visualize the problem. When building a real system, always prototype it on paper and analyze its function *before* constructing it.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults.
- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Often you can add or remove components in a malfunctioning system to simplify it as well and better identify the nature and location of the problem.
- Work "backward" from a hypothetical solution to a new set of given conditions.

How to create more time for study:

- Kill your television and video games. Seriously – these are incredible wastes of time. Eliminate distractions (e.g. cell phone, internet, socializing) in your place and time of study.
- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin studying the next day's material.

Above all, cultivate persistence. Persistent effort is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

file `question0`

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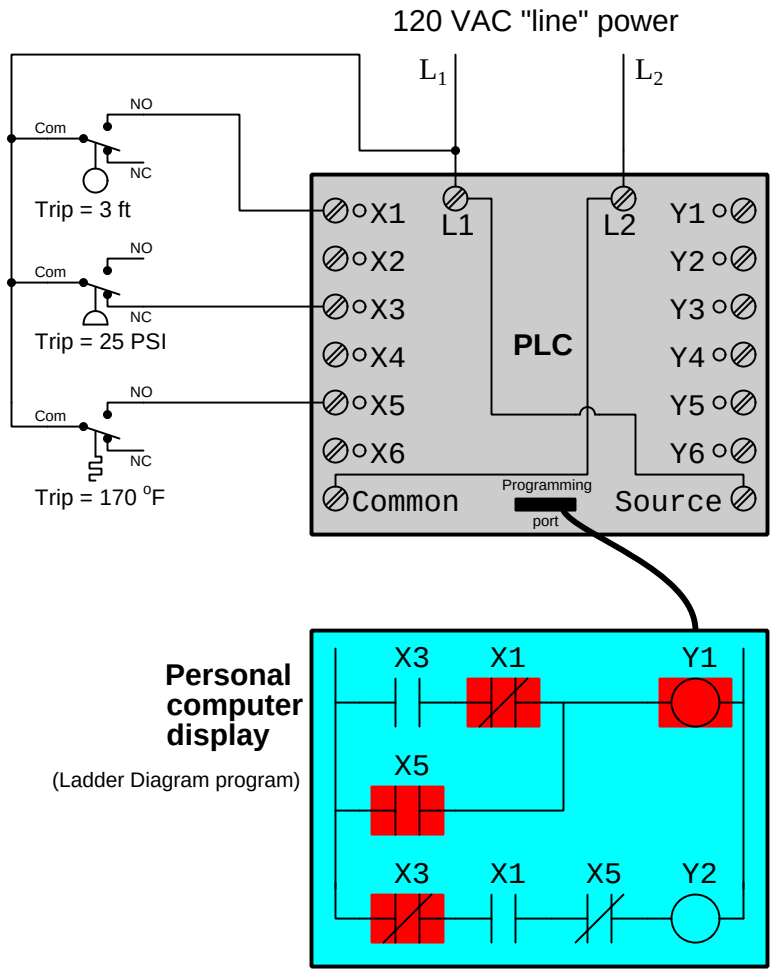
file `license`

Question 1

Suppose we have a PLC connected to two process switches as shown in this illustration:



Based on the highlighting you see in the "live" PLC program display, determine as best you can the pressure and temperature stimulating each switch:

Suggestions for Socratic discussion

- Identify which LED indicators on the PLC's face would be lit in this condition.

file i01879

Question 2

Read selected portions of the Siemens "SIMATIC S7-200 Programmable Controller System Manual" (document A5E00307987-04, August 2008) and answer the following questions:

Identify the different types of SIMATIC *timer* instructions, explaining how each one functions.

Identify a practical application for a timer instruction programmed into a PLC.

How long can one of these timer instructions time up to? Based on this maximum value, how many bits do you think are used in the register to store a timer instruction's current value?

What is meant by the *resolution* of a timer instruction? How many different options do the SIMATIC instructions provide for resolution?

Comment on how a SIMATIC timer's value is updated in a PLC program if the resolution is 1 ms, if it is 10 ms, and if it is 100 ms. The Siemens S7-200 PLC handles each one differently!

Sketch a simple ladder-diagram program for a Siemens S7-200 PLC whereby a switch connected to input `I0.3` causes a timer to increment (count *up*) and then turn on an alarm light output `Q0.9` after 5 seconds.

Suggestions for Socratic discussion

- If you have access to your own PLC for experimentation, I urge you to write a simple *demonstration* program in your PLC allowing you to explore the behavior of these PLC instructions. The program doesn't have to do anything useful, but merely demonstrate what each instruction does. First, read the appropriate section in your PLC's manual or instruction reference to identify the proper syntax for that instruction (e.g. which types of data it uses, what address ranges are appropriate), then write the simplest program you can think of to demonstrate that function in isolation. Download this program to your PLC, then run it and observe how it functions "live" by noting the color highlighting in your editing program's display and/or the numerical values manipulated by each instruction. After "playing" with your demonstration program and observing its behavior, write comments for each rung of your program explaining in your own words what each instruction does.
- Why do you suppose Siemens designed their timer instructions to update their current values differently, depending on the programmed resolution of the timer? Why not make all timer instructions update similarly, regardless of resolution?

file i00229

Question 3

Read selected portions of the Allen-Bradley "MicroLogix 1000 Programmable Controllers (Bulletin 1761 Controllers)" user manual (document 1761-6.3, July 1998) and answer the following questions:

Identify the different types of *timer* instructions available in the MicroLogix 1000 controller, explaining how each one functions. How do these types compare with those offered in the Siemens S7-200 PLC?

Identify a practical application for a *retentive* timer instruction programmed into a PLC.

How many different options do the Allen-Bradley MicroLogix timer instructions provide for resolution?

How long can one of these timer instructions time up to? Based on this maximum value, how many bits do you think are used in the register to store a timer instruction's current value?

Sketch a simple ladder-diagram program for an Allen-Bradley MicroLogix 1000 PLC whereby a switch connected to input `I:0/2` causes a timer to increment (count *up*) and then turn on an alarm light output `O:0/1` after 5 seconds.

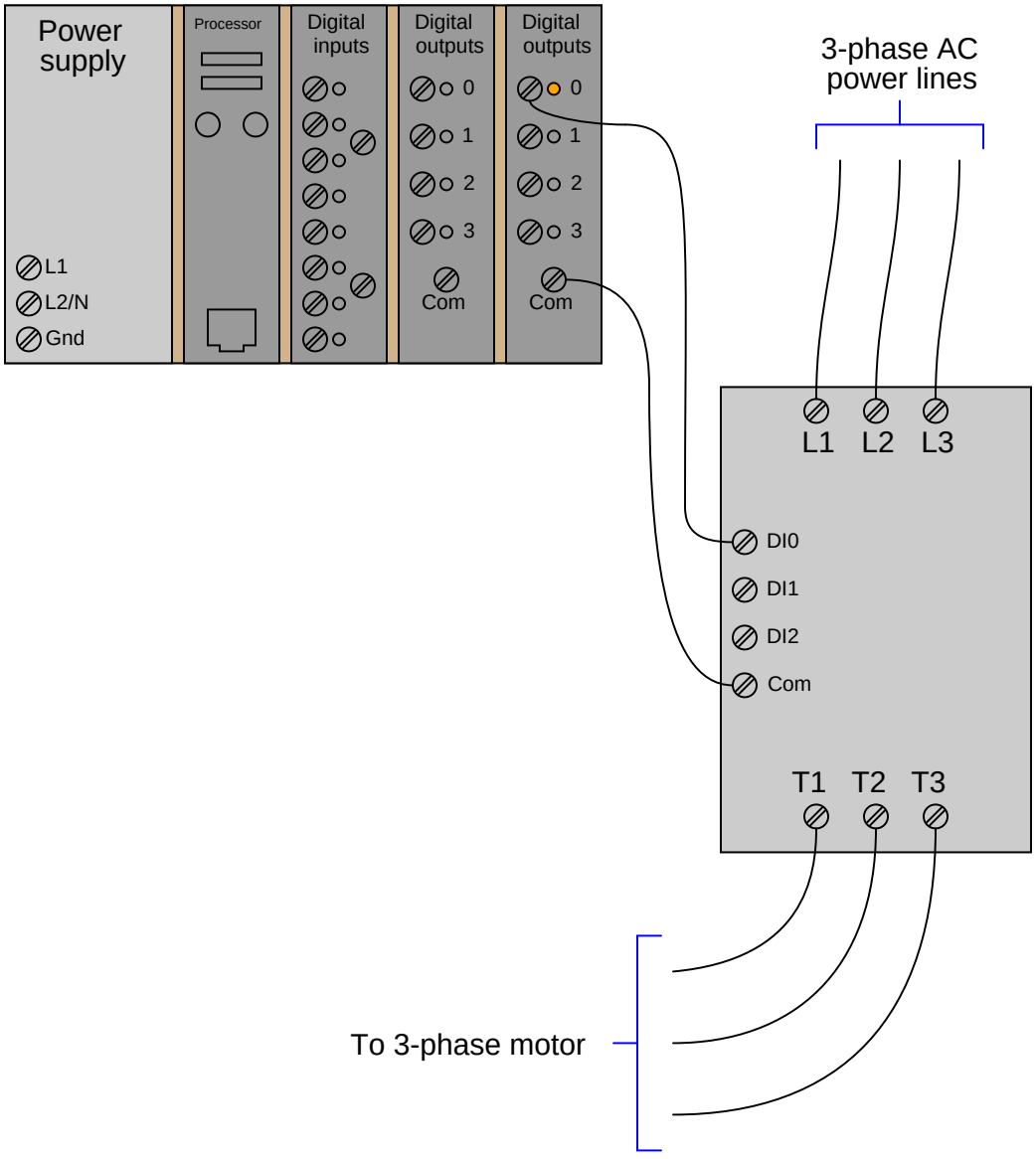
Suggestions for Socratic discussion

- If you have access to your own PLC for experimentation, I urge you to write a simple *demonstration* program in your PLC allowing you to explore the behavior of these PLC instructions. The program doesn't have to do anything useful, but merely demonstrate what each instruction does. First, read the appropriate section in your PLC's manual or instruction reference to identify the proper syntax for that instruction (e.g. which types of data it uses, what address ranges are appropriate), then write the simplest program you can think of to demonstrate that function in isolation. Download this program to your PLC, then run it and observe how it functions "live" by noting the color highlighting in your editing program's display and/or the numerical values manipulated by each instruction. After "playing" with your demonstration program and observing its behavior, write comments for each rung of your program explaining in your own words what each instruction does.
- Some of the addressing examples given in the Allen-Bradley MicroLogix 1000 manual for timer instructions use forward-slash characters (`/`) while other examples use dot characters (`.`) to delimit the last portion of the address. What do these different characters mean in Allen-Bradley addressing? For example, what is the different between `T4:0/EN` and `T4:0.ACC`? Why must the "EN" be preceded by a forward slash while the "ACC" is preceded by a dot?

file i00247

Question 4

A technician is troubleshooting a problem with a newly-installed PLC and variable-speed motor drive. One of the discrete (on/off) outputs of the PLC is connected to a discrete input on the drive, to tell the motor to either turn on or turn off. The PLC's discrete output is a *dry contact* type, meaning it is nothing more than an electromechanical relay contact inside the output card. The discrete inputs on the drive (DI0, DI1, and DI2) are logic gate inputs, internally "pulled up" with resistors so that the only thing needed to activate each input is to form a connection between the respective input and the common ("Com") terminal on the drive. The dry contact for PLC output 0 on the right-most output card is supposed to do just that, telling the drive when to start the motor:



The problem is, the motor does not start when the PLC tells it to. Now, the motor itself is brand-new, and the wiring between the motor and the drive is known to be good. A power check at the PLC and drive power terminals shows 117 volts AC between L1 and L2/N (on the PLC) and 482 volts between each of the three phases (L1, L2, and L3) on the motor drive. The LED indicator for output 0 on the PLC card is lit,

revealing that the PLC program at least is *trying* to activate the motor drive. This data suggests (but does not guarantee) that the problem lies either with the PLC hardware or the drive, and not with the power sources, motor wiring, motor, PLC inputs, or PLC program.

Both the PLC and the motor drive are complex, programmable devices. The technician knows she could spend quite a bit of time diagnosing either of these devices trying to find a problem. Thus, it would be very helpful to know *which* of these devices is at fault so as to not waste troubleshooting time.

Devise a simple test for the technician to perform that will neatly divide the problem in half, telling her whether the PLC or the drive is at fault, and be sure to explain your reasoning.

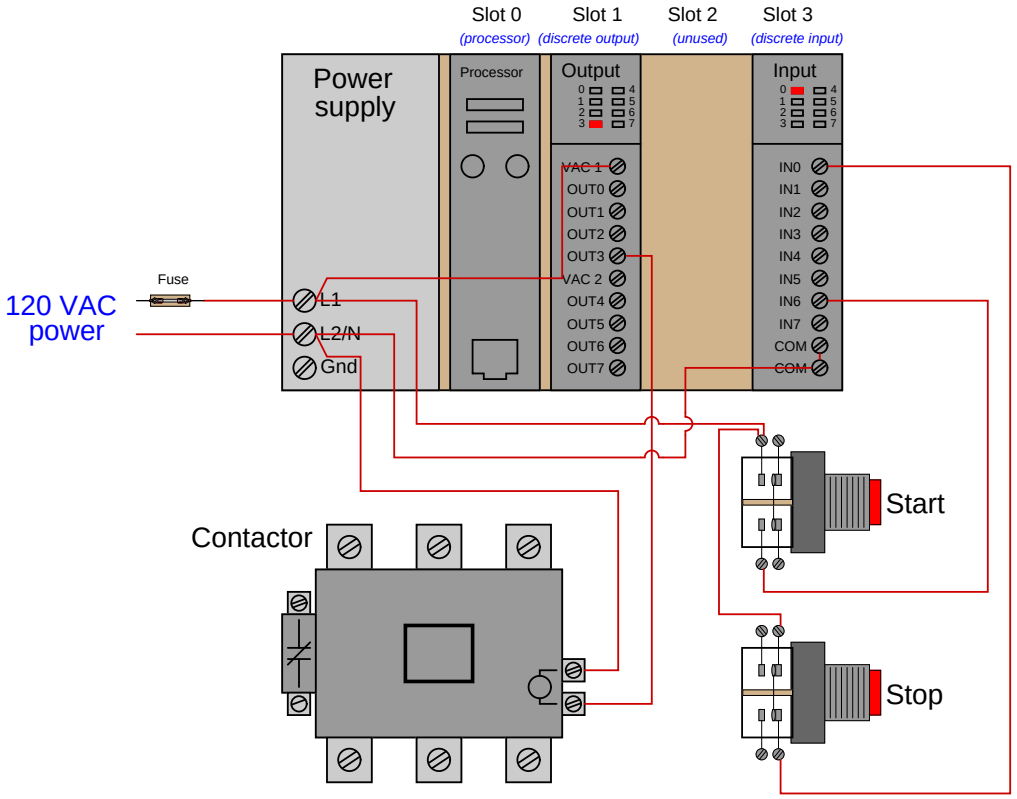
Suggestions for Socratic discussion

- Is the PLC output card *sourcing* curren to or *sinking* current from the VFD in this system?
- If the problem lies within the PLC, where exactly do you think it might be found within the PLC? Do you think it could be a hardware problem, a software problem, or either?

file i02451

Question 5

An Allen-Bradley SLC 500 PLC is used to control a motor, using an across-the-line starter. All 480 volt power wiring in this PLC-controlled "bucket" has been omitted for simplicity:



After many years of trouble-free operation, the motor refuses to start. You have no test equipment with you – all you have is what you see in the above illustration (with neither pushbutton pressed at the time).

Identify the likelihood of each specified fault in this system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* observations and symptoms in this circuit.

Fault	Possible	Impossible
Open wire between Start switch and IN6 terminal		
Open wire between Stop switch and IN0 terminal		
Open contactor coil		
Shorted contactor coil		
Start switch incorrectly wired		
Failed input card		
Failed output card		
PLC program halted		
Blown fuse		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

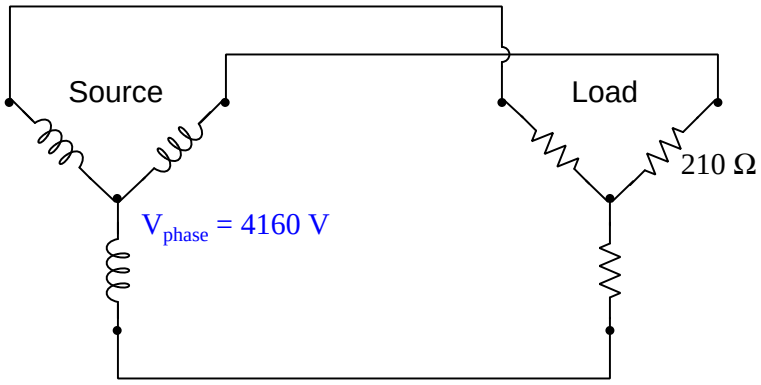
Suggestions for Socratic discussion

- Suppose we needed to perform some diagnostic tests on the Start and Stop switch input wiring which required actuating those switches repeatedly, but we did not want to actually start up the motor. Explain how we could use the *force* utility in the PLC to accomplish this goal, and why it is very important we disable all of our imposed "forces" when the job is done.

  file i02260

Question 6

Calculate all voltages, currents, and total power in this balanced Y-Y system:



- E_{line} =
- I_{line} =
- $E_{phase(source)}$ =
- $I_{phase(source)}$ =
- $E_{phase(load)}$ =
- $I_{phase(load)}$ =
- P_{total} =

Suggestions for Socratic discussion

- Explain how you may double-check your quantitative answer(s) with a high degree of confidence (i.e. something more rigorous than simply re-working the problem again in the same way).
- Identify the effects on these voltage and current values if one of the load resistors fails open.

  file i02435

Question 7

Demonstration Program – timer instructions

An important technique for learning any programming language – Ladder Diagram PLC programming included – is to write simple "demonstration" programs showcasing and explaining how particular instructions and programming constructs are supposed to work. Since you have access to your own personal PLC, you can explore the elements of your PLC's programming language like a scientist would explore new specimens: subject them to tests and record how they respond. This is how you will be able to teach yourself new models of PLC when you are working in your career, when you won't have textbooks to follow or training to show you exactly what to do.

Write such a "demonstration" program for your PLC's *timer* instructions, where discrete inputs on your PLC control discrete outputs on your PLC. An acceptable demonstration program must meet these three criteria:

- **Simple** – nothing "extra" included in the program to detract from the fundamental behavior of the instruction(s) being explored
- **Complete** – nothing missing from the program relevant to the fundamental behavior of the instruction(s) being explored. *For a timer demonstration program, this includes on-delay timers, off-delay timers, and retentive timers.*
- **Clearly documented** – every rung clearly commented in your own words, every variable named

Your instructor will challenge you to use this demonstration program to illustrate what you have learned about PLC counter instructions.

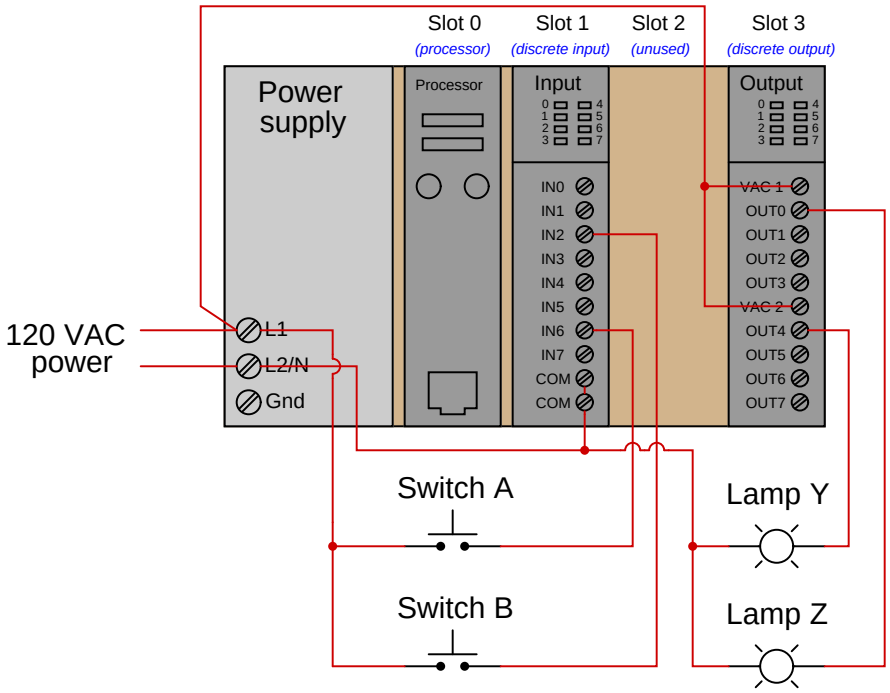
Suggested questions your demonstration program should answer:

- What are the different timer instruction types offered on your PLC? What does each one of them do?
- Where in the PLC's memory is each timer storing its data?
- Where in the PLC programming editor can you view the "live" status of a timer instruction?
- What are the "timebase" options for timers in your PLC? How fast or slow can they time?
- How long of a time period can a timer time? What is the maximum "count" value for a timer?
- When a timer instruction reaches its preset (setpoint) value, does it keep timing or does it stop at that value?
- How does the operation of an off-delay timer differ from that of an on-delay timer?
- How does the operation of a retentive on-delay timer differ from that of a non-retentive on-delay timer?
- How does each type of timer get reset?
- When a timer instruction is reset, does its current value go to zero or one?
- How does each type of timer get to control something, like an output bit?
- Is it possible to "preload" a timer instruction so that it doesn't have to begin at the starting value when the PLC program runs anew?
- What happens to the timer's current value when it reaches its maximum value? Does the timer instruction stop timing, or does it do something else?

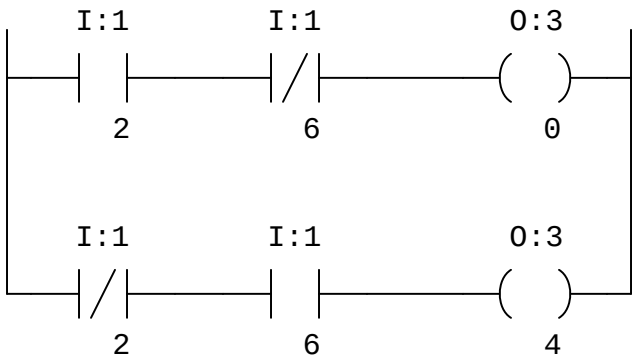
file i03692

Question 8

Suppose we have an Allen-Bradley model "SLC 500" PLC connected to a pair of momentary-contact pushbutton switches and light bulbs as shown in this illustration:



Examine the following relay ladder logic (RLL) program for this Allen-Bradley PLC, determining the statuses of the two lamps provided switch A is pressed by a human operator and switch B is unpressed:



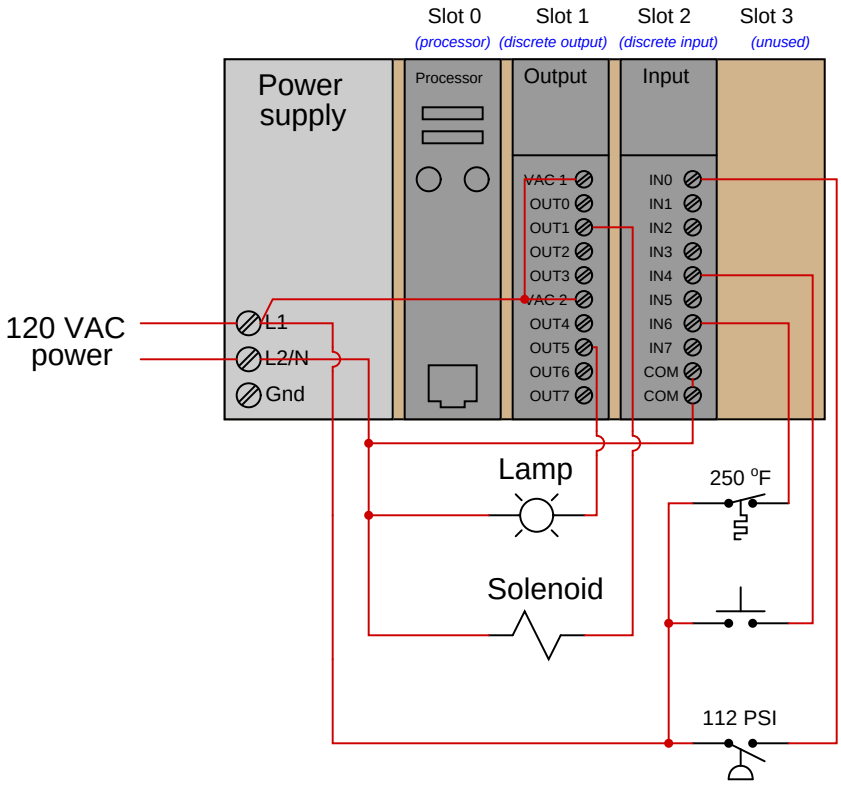
Suggestions for Socratic discussion

- Identify which LED indicators on the I/O cards' faces would be lit in this condition.
- Describe how this system would respond if a technician used the *force* utility to force bit `O:3/4` to a "1" state in the PLC's memory.

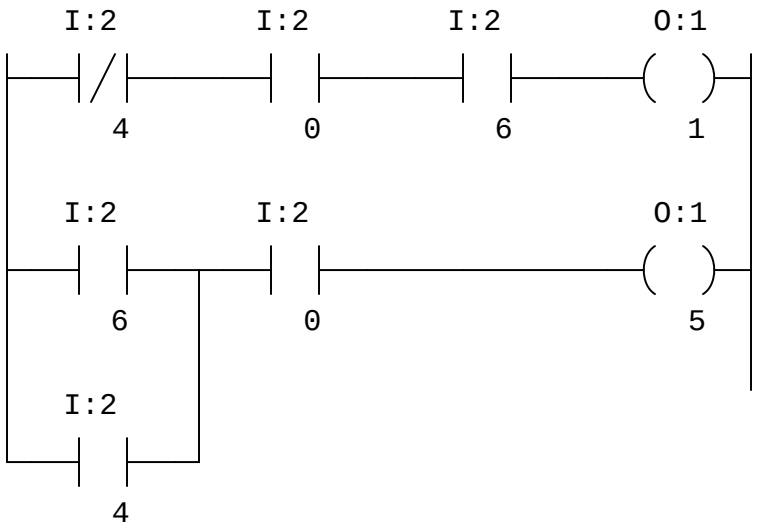
file i03760

Question 9

Suppose we have an Allen-Bradley model "SLC 500" PLC connected to a three switches and two AC loads (a lamp and a solenoid coil) as shown in this illustration:



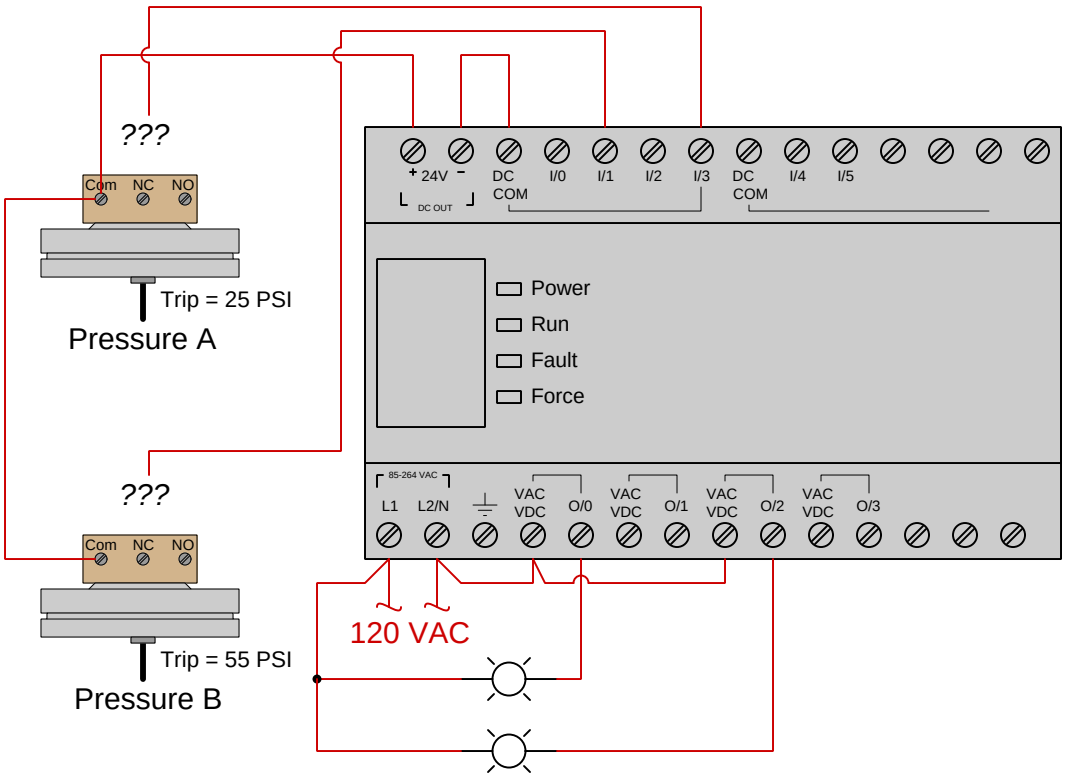
The following is the PLC's program as it appears printed on paper. From this information, determine the status of the lamp and of the solenoid coil provided a process pressure of 130 PSI, a process temperature of 186 ^{o}F, and an unpressed pushbutton switch:



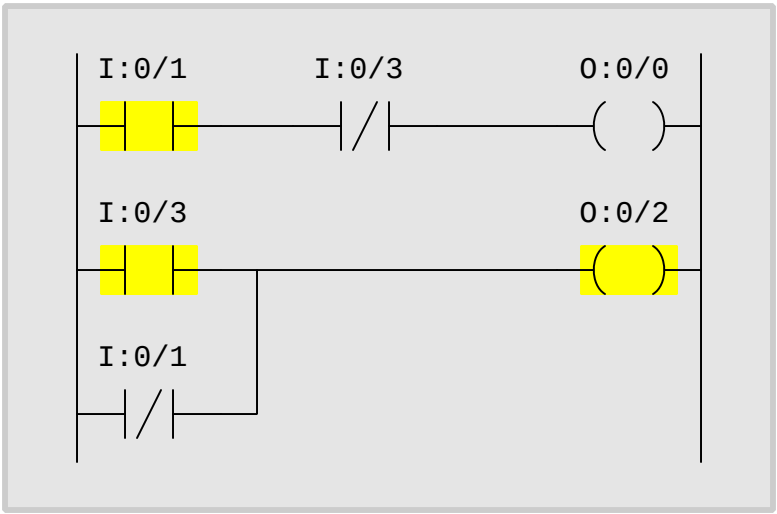
file i04527

Question 10

Choose the appropriate switch terminals to land wires connecting the two pressure switches to the PLC in order to satisfy the requirements of the "online" program display (showing color highlighting), assuming pressure A is 14 PSI and pressure B is 70 PSI:



Online PLC program display



file i02882

Question 11

Programming Challenge – Reaction time measurement

Program your PLC to measure a person's reaction time in flipping a switch. The PLC should energize a light (or simply one of the discrete output indicating LEDs) telling the user when to flip an input switch, and then the PLC will measure how long it takes for the person to react to the light and flip the switch.

Suggestions for Socratic discussion

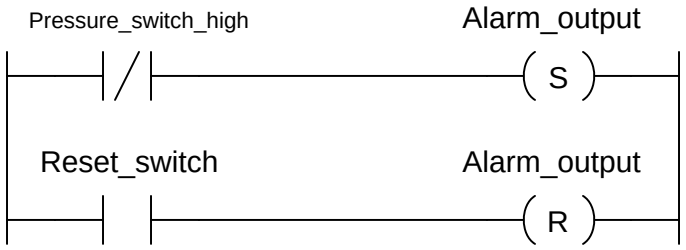
- How can you program the PLC to turn on the signaling light in a way that the person being tested cannot anticipate it?
- How must you configure the reaction time timer to count in units appropriate for this very quick time delay?
- What type of timer instruction is best suited for the reaction time timer, a *retentive* or a *non-retentive* timer?

file i02266

Question 12

Programming Challenge – Alarm event latch and history timers

A normally-closed (NC) high-pressure sensing switch monitors fluid pressure in a chemical reactor vessel, opening its contacts if the pressure exceeds the trip point. This triggers an alarm lamp to energize in the control room, and this lamp will latch in the "on" state until an operator resets it, even if the high-pressure condition "clears" and goes back to normal. This is so the operators will know a high-pressure event occurred even if they were not in the control room to see it when it happened. A PLC implements this latching function using retentive ("set" and "reset") coils:



The system works well, but the operators want more. If they arrive at the control room to see the alarm light on (latched), they want to know how long the high-pressure condition lasted and also how long it's been since the reactor pressure returned to normal.

Add instructions to this PLC program to provide the desired timing functionality.

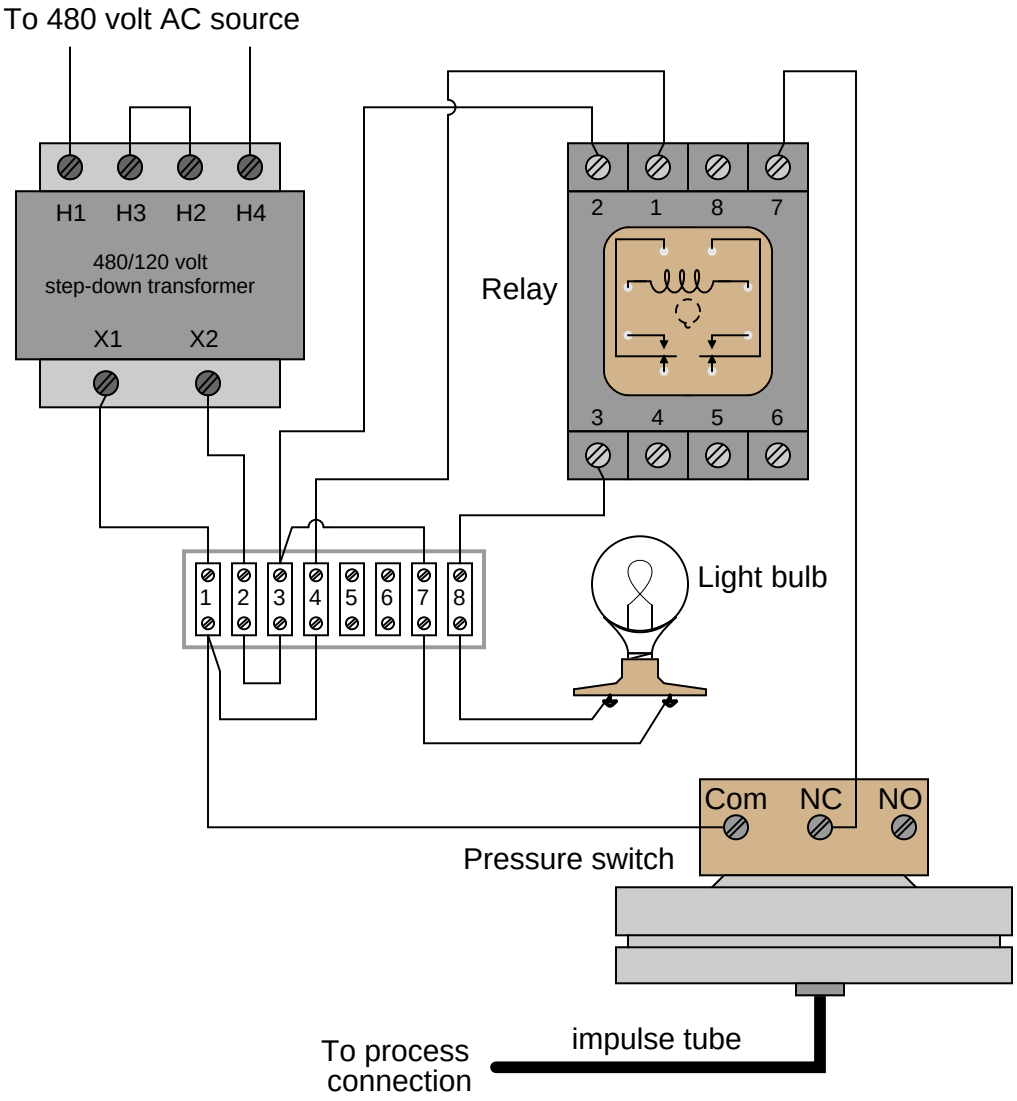
Suggestions for Socratic discussion

- Explain why the PLC program contact for the high-pressure switch is *normally-closed*, and how this information alone would be enough for us to determine that the high-pressure switch itself had NC contacts.
- What type of timer instruction is best suited for the event duration timer, a *retentive* or a *non-retentive* timer?
- How could a *counter* instruction be added to this PLC program to provide useful functionality?

file i02265

Question 13

This is a pressure alarm circuit, designed to energize a warning light if the process pressure sensed by the pressure switch ever crosses a certain threshold value:



First, determine if this is a *low-pressure* alarm or a *high-pressure alarm* (i.e. under what type of process pressure condition will the light bulb energize, an abnormally low pressure or an abnormally high pressure?).

Next, determine the effect of a bad wire connection ("open" fault) at terminal 2 of the control relay on the status of the warning light.

Suggestions for Socratic discussion

- Identify how the circuit could be altered to alarm in the opposite condition it does now (i.e. high pressure instead of low pressure, or low pressure instead of high pressure, whichever you have determined the circuit to be in its present configuration).

file i04508

Question 14

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Identify any area(s) of your study in which you would like to become stronger. Examples include technical reading, electrical circuit analysis, solving particular types of problems, time management, and/or skills applied in the lab. Cite specific examples if possible, and bring these to your instructor's attention so that together you may target them for improvement. As a starting point, try consulting the list of topics on the first page of the worksheet for the upcoming mastery exam, as well as the "General Values and Expectations" list near the beginning of the worksheet identifying the habits and qualities necessary for success in this career.

Next, identify practical strategies you will use to strengthen these areas. Examples include focusing on specific types of problem-solving whenever those types appear in the homework, working through practice problems for a particular subject, and/or coordinating with your lab team to give you more practice on specific skills.

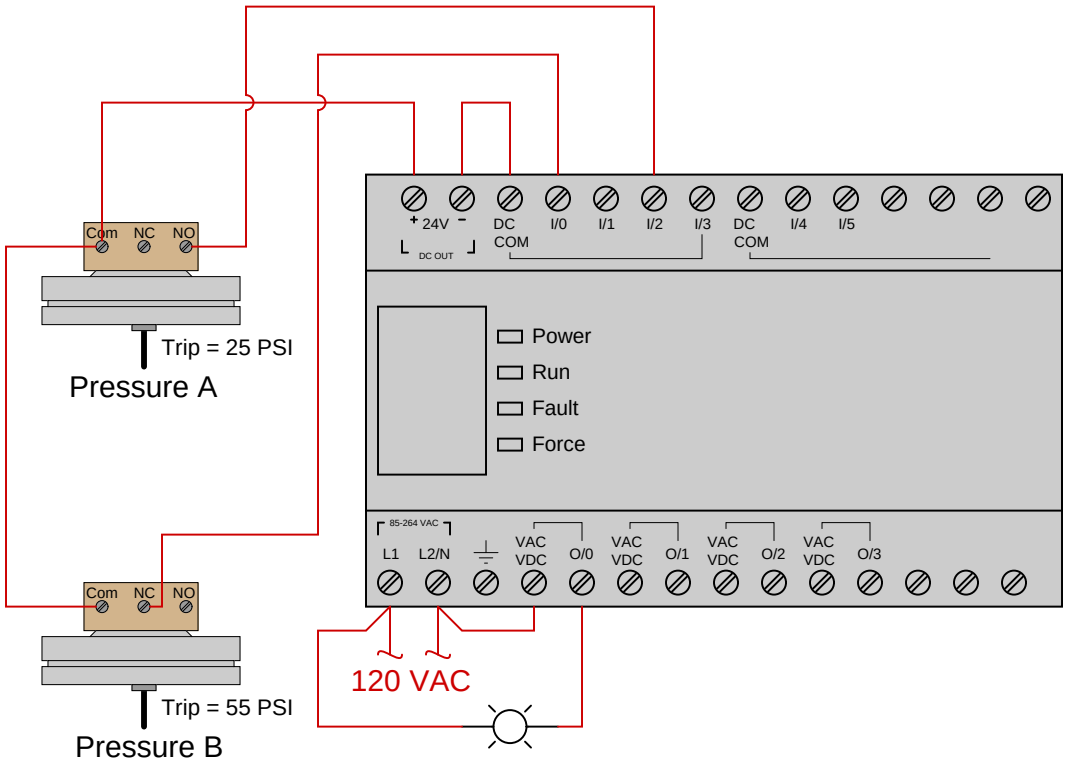
Suggestions for Socratic discussion

- One useful strategy is to maintain a *journal* of all you've learned in a course of study. Explore ways you could take the work you're already doing to prepare for homework (daily discussions with your instructor) and turn this into a journal or even a weblog ("blog") for your own reflection and eventual use as a portfolio to showcase your capabilities to employers.
- Where exactly are the practice problem worksheets located on the *Socratic Instrumentation* website?

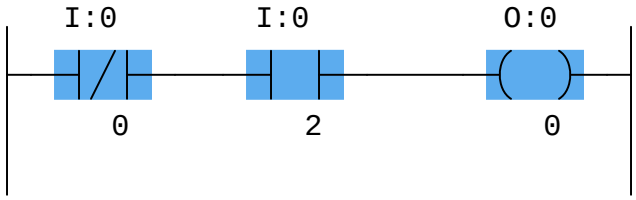
  file i00999

Question 22

Suppose we have an Allen-Bradley MicroLogix 1000 PLC with two pressure switches connected to it:



Determine the applied fluid pressures to these switches based on their electrical connections and the status highlighting seen in a "live" display of the PLC's program:



Also, determine whether the PLC inputs in this system are *sourcing* or *sinking* current.

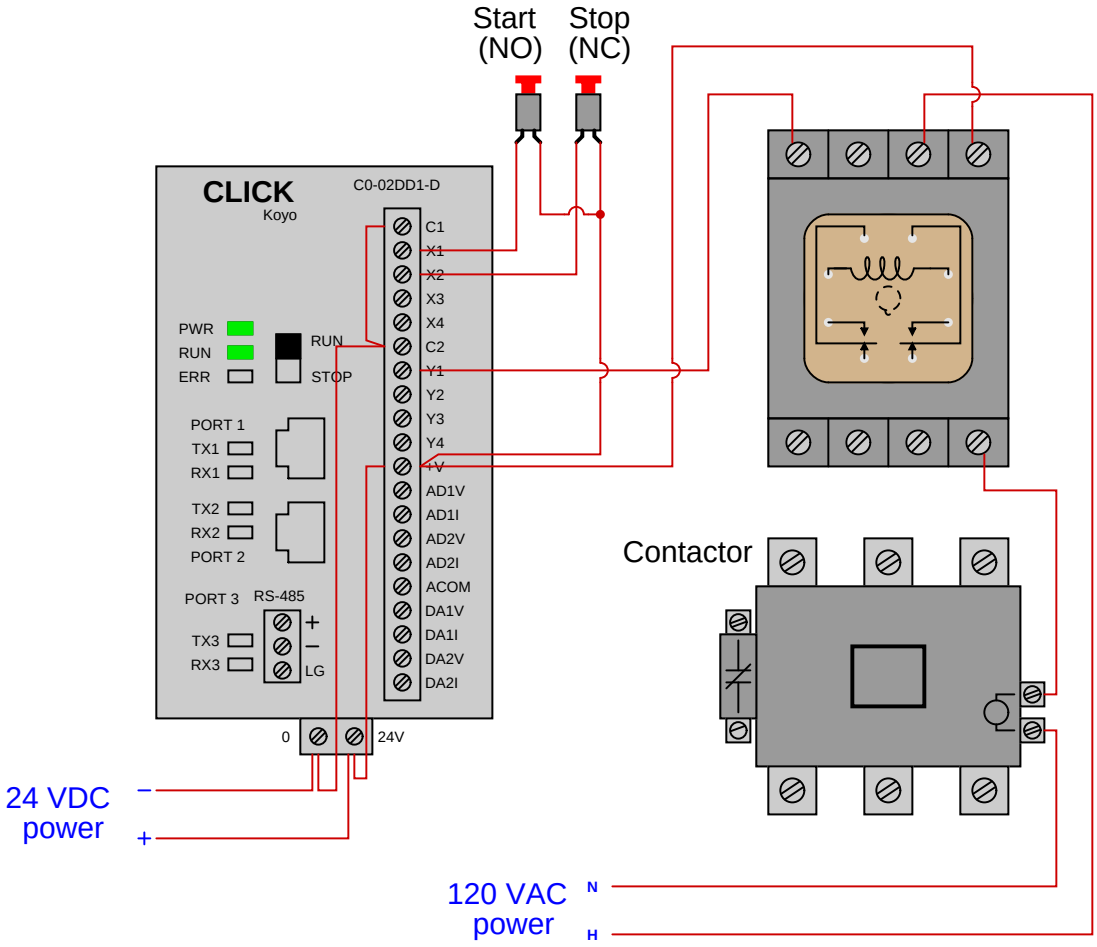
Suggestions for Socratic discussion

- Explain how we could use the *force* utility in the PLC to keep the lamp energized at all times regardless of switch status, and why it is very important we disable all of our imposed "forces" when finished with this task.

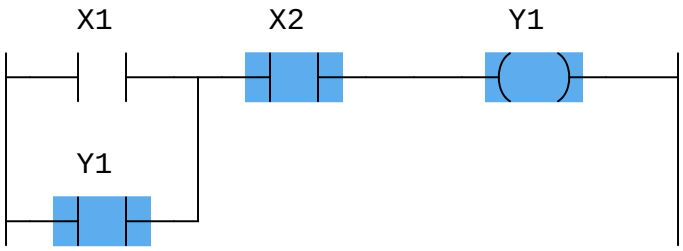
  file i02261

Question 23

Suppose we have a Koyo "CLICK" PLC controlling an AC induction motor though a contactor. The motor's 480 VAC three-phase wiring and the power sources have been eliminated from this diagram for simplicity:



Unfortunately, the motor is not starting up when it should. You are summoned to investigate, so you connect a laptop PC to the PLC to examine the "live" status of the program elements:

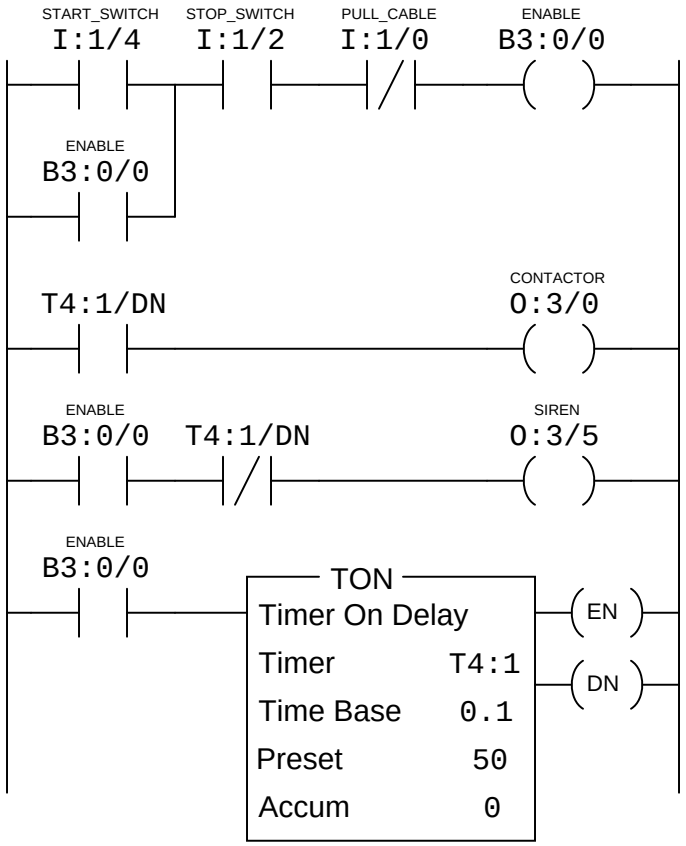


Based on your examination of this program, identify some likely faults to explain why the motor is not starting, and describe your next diagnostic step(s) in isolating the exact nature and location of the problem. Also, determine whether the `Y1` output is *sourcing* or *sinking* current.

file i02268

Question 24

Suppose an Allen-Bradley PLC controls the starting and stopping of a conveyor belt, using a timer to sound an audible warning siren for 5 seconds before the conveyor belt starts up (to warn people before the belt begins to move):



Determine the necessary contact connections (form-A or form-B) on the real-life Start, Stop, and emergency Pull-Cable switches to complement the virtual contact types in the PLC program.

Start switch = form-A *or* form-B?

Stop switch = form-A *or* form-B?

Pull-Cable switch = form-A *or* form-B?

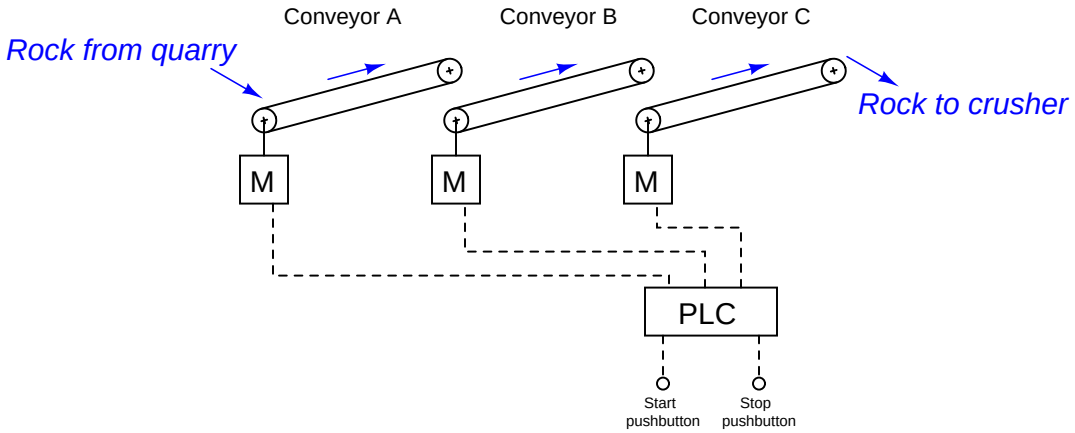
Suggestions for Socratic discussion

- How could you modify this program so that the operator has to hold the "Start" pushbutton switch actuated for the duration of the warning siren before the motor would start (i.e. everything would simply stop if the operator only *momentarily* pressed the "Start" button)?
- Suppose a technician decides to use the *force* utility in the PLC to force bit `B3:0/0` to a "0" state in order to test the warning siren's operation without actually starting up the conveyor belt. Explain what is flawed with this testing strategy, and identify a better approach.
- How will this system behave if the pull-cable switch fails open?
- How will this system behave if the stop switch fails shorted?

file i02259

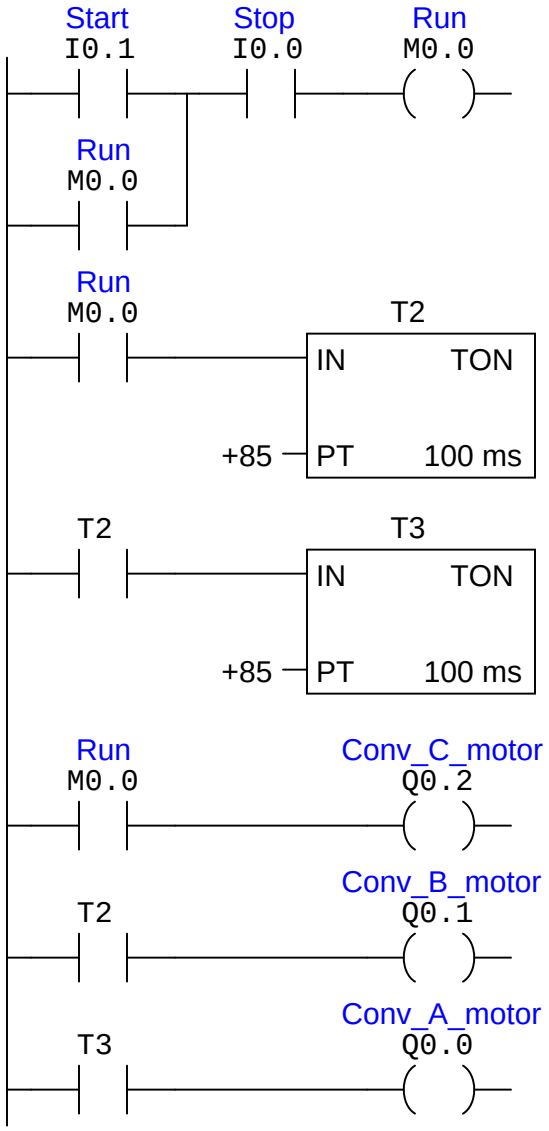
Question 25

A gravel-crushing operation uses three long conveyor belts to move rock from the quarry to the crusher. The belts must be started up in a particular sequence to avoid overloading the electric motors driving them:



First, determine a start-up sequence that makes sense: which conveyor belt should start first, next, and last? What might happen if the sequence were reversed? Why not simply start all conveyor motors simultaneously?

This operation uses a Siemens S7 series PLC to control the three conveyor belts. Analyze this program and explain how it accomplishes the task of starting up the three conveyors in sequence:



Lastly, determine where you might add a contact instruction for an *emergency shutoff* safety switch, so that all three conveyors stop simultaneously if ever the safety switch is actuated.

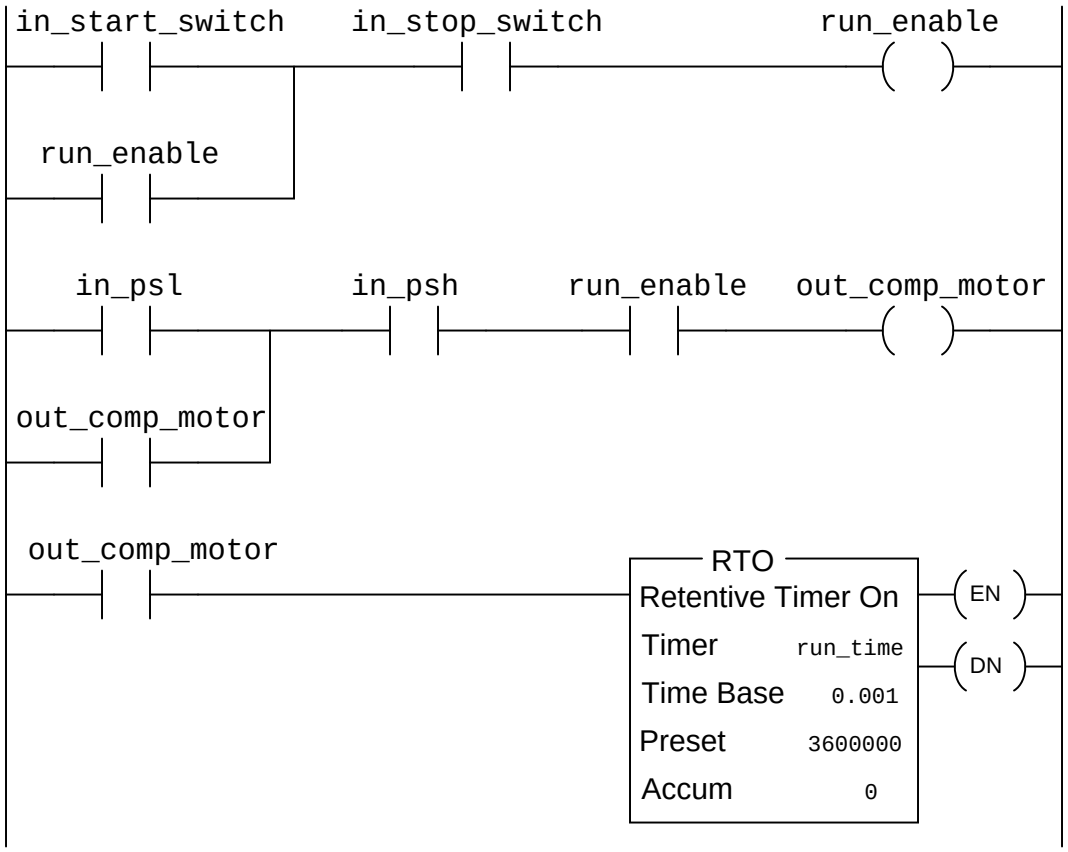
Suggestions for Socratic discussion

- How long is the time delay between conveyor start-ups? How might this time delay be altered if needed?
- Suppose a warning siren were added to the system, sounding for a full 15 seconds before the first conveyor belt starts. How would you modify the PLC program to include this additional functionality?
- Suppose a technician uses the PLC's *force* utility to force bit `T2` to a "0" state. How will this affect the operation of the system? Could the consequences of this force be dangerous in any way?
- Suppose a technician uses the PLC's *force* utility to force bit `Q0.1` to a "0" state. How will this affect the operation of the system? Could the consequences of this force be dangerous in any way?

file i04428

Question 26

An Allen-Bradley Logix5000 PLC is used to control the starting and stopping of an air compressor based on momentary-contact pushbutton switch inputs as well as high and low pressure switches (PSH and PSL, respectively). Analyze this program and explain how it is supposed to work:



(continued on next page)

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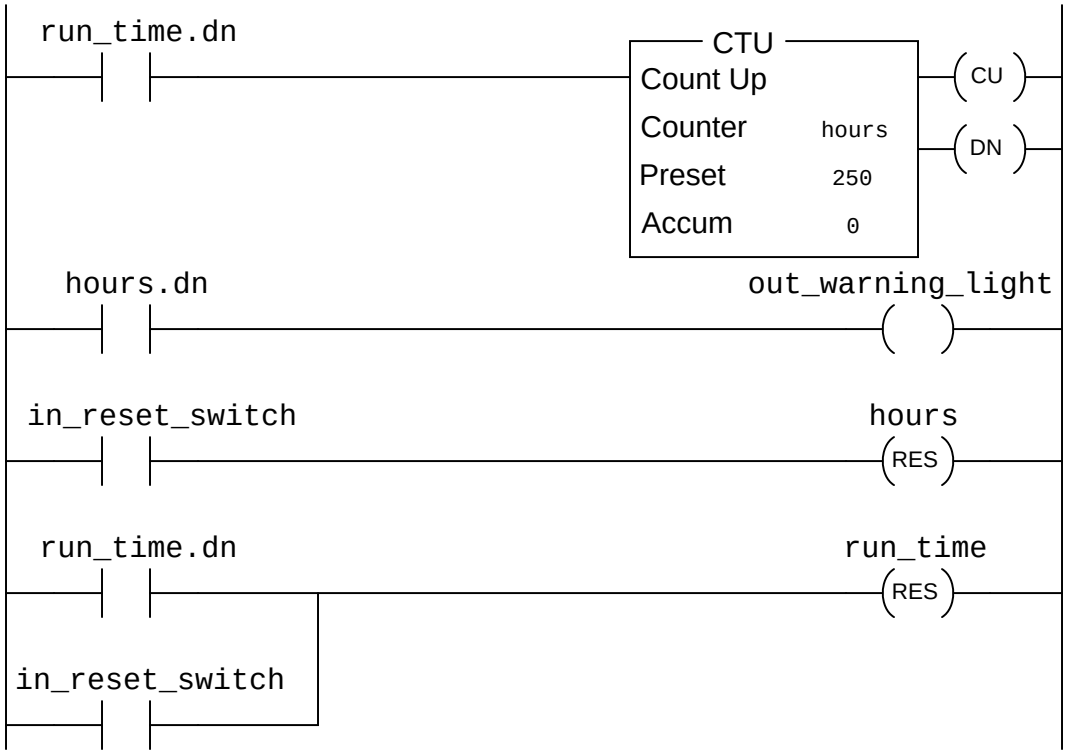


In particular, answer these following questions:

- Determine the "normal" electrical statuses of all switches (e.g. NO or NC) connected to the inputs of this PLC, based on an examination of the respective contact instructions within the PLC program.
- Why is is important that a *retentive* timer instruction be used for the calculation of total run-time?
- What is the significance of the maintenance warning light controlled by this PLC?

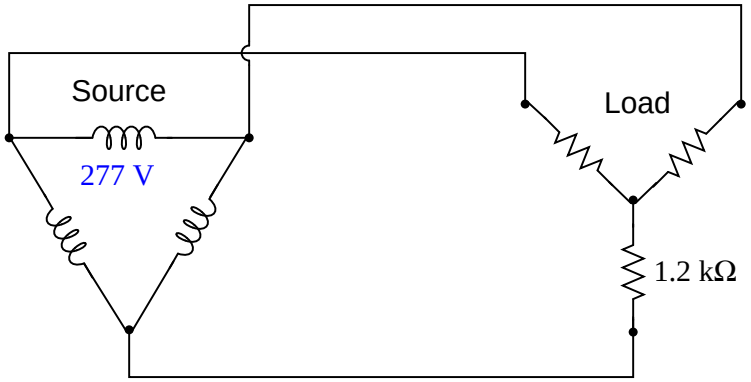
Suggestions for Socratic discussion

- Note how all instructions in this Logix5000 PLC program are addressed by *tagname* rather than by hardware addresses (e.g. `I:2/6`, `O:3/1`). How do you suppose the PLC "knows" which real I/O points to associate with which instructions in the program?
- How will this system behave if the reset switch fails shorted?
- How will this system behave if the high-pressure switch fails open?
- How will this system behave if the high-pressure switch fails shorted?
- How will this system behave if the low-pressure switch fails open?
- How will this system behave if the low-pressure switch fails shorted?

file i02346

Question 27

Calculate all voltages, currents, and total power in this balanced Delta-Wye system:



- E_{line} =
- I_{line} =
- $E_{phase(source)}$ =
- $I_{phase(source)}$ =
- $E_{phase(load)}$ =
- $I_{phase(load)}$ =
- P_{total} =

Suggestions for Socratic discussion

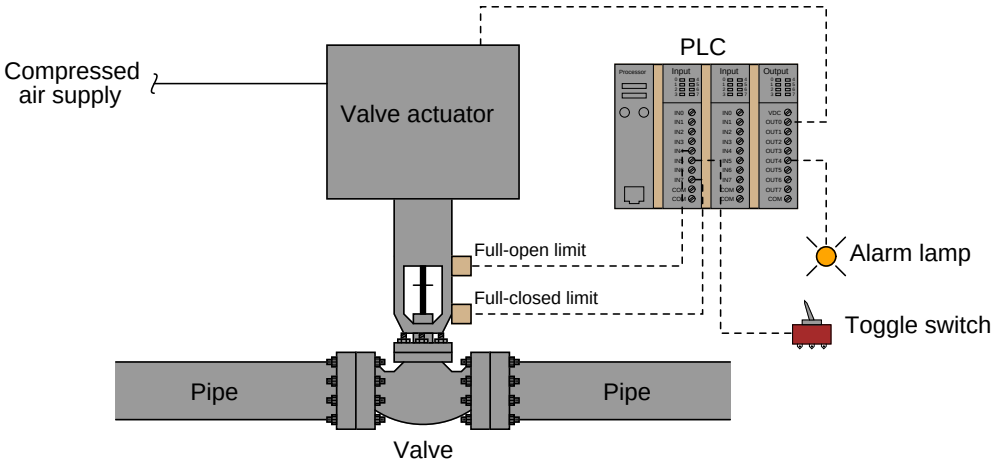
- Explain how you may double-check your quantitative answer(s) with a high degree of confidence (i.e. something more rigorous than simply re-working the problem again in the same way).
- Identify the effects on these voltage and current values if one of the load resistors fails open.

file i02430

Question 28

Programming Challenge and Comparison – solenoid valve control with stuck valve alarm

A PLC is used to control the opening and closing of a solenoid-operated valve with a single discrete output. A pair of normally-open limit switches sense the valve's stem position:



Write a PLC program energizing an alarm lamp if the valve fails to reach the full-open position within 5 seconds of receiving the "open" command signal, and energizing the same alarm lamp if the valve fails to reach the full-closed position within 8 seconds of receiving the "close" command signal. Note that the status of both limit switches will be "open" (off) when the stem is between its full-open and full-closed positions. The PLC receives the command to open or close the valve from a hand-operated toggle switch.

Inputs

- Open/Close toggle – *off when commanding valve to shut ; on when commanding valve to open wide*
- Valve closed limit (NO) – *closes when valve reaches 0% position*
- Valve open limit (NO) – *closes when valve reaches 100% position*

Outputs

- Valve actuator solenoid – *energizing this coil opens up the valve, de-energizing this coil allows the valve to spring-return shut*
- "Valve stuck" alarm lamp – *energize if valve does not respond in time*

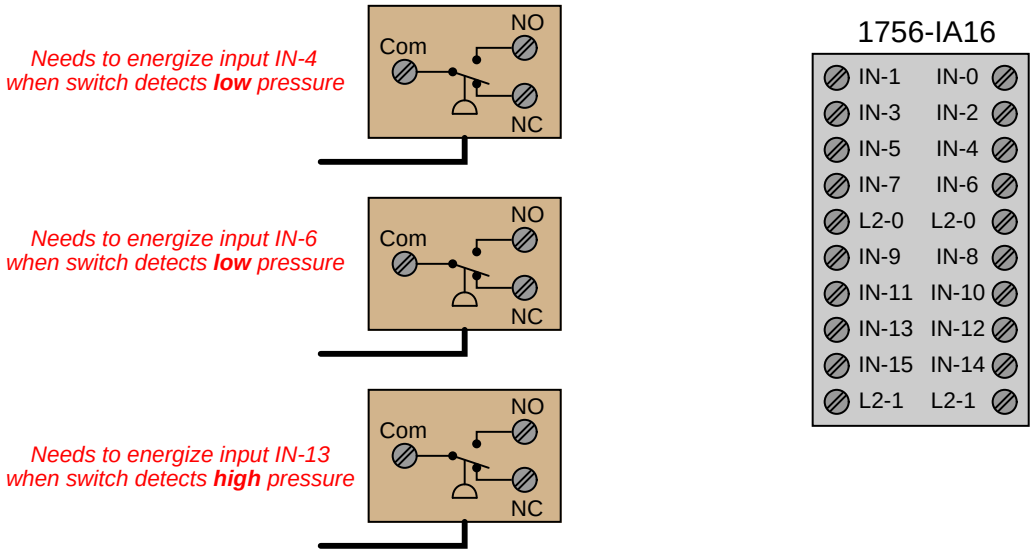
When your program is complete and tested, capture a screen-shot of it as it appears on your computer, and prepare to present your program solution to the class in a review session for everyone to see and critique. The purpose of this review session is to see multiple solutions to one problem, explore different programming techniques, and gain experience interpreting PLC programs others have written. When presenting your program (either individually or as a team), prepare to discuss the following points:

- Identify the "tag names" or "nicknames" used within your program to label I/O and other bits in memory
- Follow the sequence of operation in your program, simulating the system in action
- Identify any special or otherwise non-standard instructions used in your program, and explain why you decided to take that approach
- Show the comments placed in your program, to help explain how and why it works
- How you designed the program (i.e. what steps you took to go from a concept to a working program)

file i04657

Question 29

Suppose you need to connect three pressure switches to channels IN-4, IN-6, and IN-13 of an Allen-Bradley model 1756-IA16 discrete input card:



Sketch the necessary wire connections to make these three pressure switches functional on the specified input channels, including any necessary power source(s) in your sketched circuit.

Note: you may find Allen-Bradley's document called *"1756 ControlLogix I/O Modules"* (publication 1756-TD002A-EN-E, May 2009) helpful in answering this question.

file i02060

Question 30

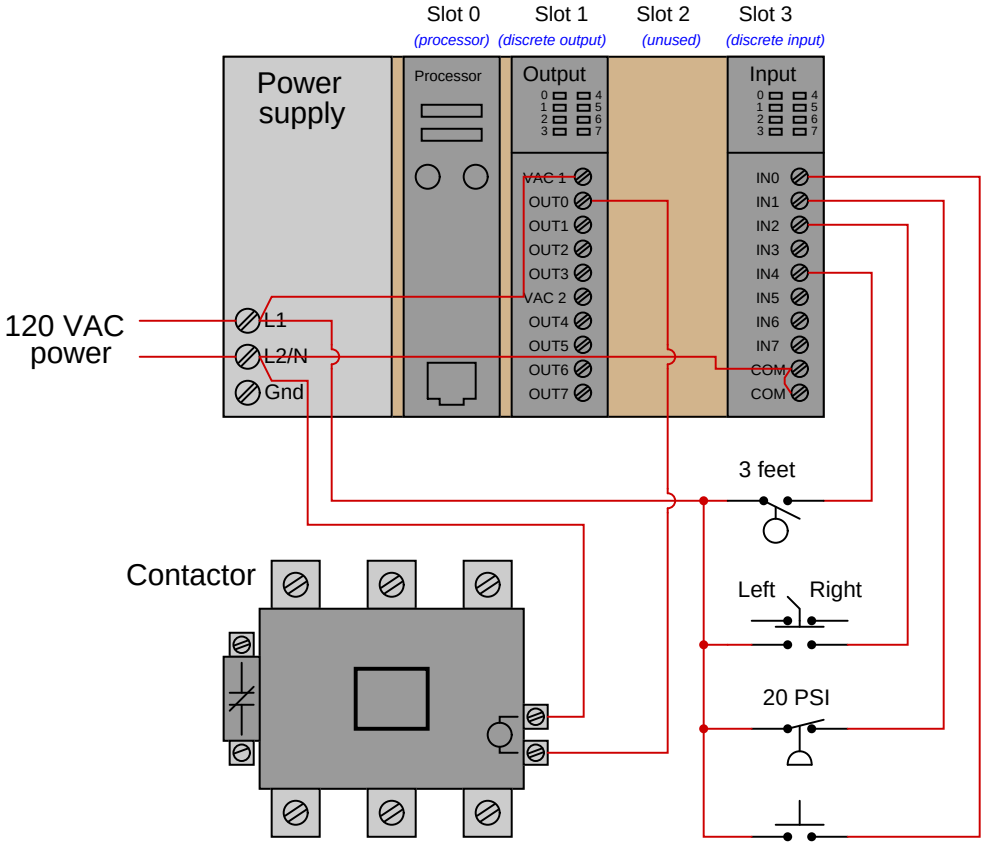
The Allen-Bradley Logix5000 family of PLCs has the option of a model 1756-IB16D DC "diagnostic" input card, where each discrete input device (switch) is supposed to be wired such that it has a 14.3 kΩ resistor connected in parallel with it.

Examine the internal schematic for a typical channel on this input card, as well as the sample wiring diagram showing how switches are supposed to be connected to the inputs of this card, and identify how this card provides "diagnostic" information above and beyond the basic recognition of switch status. Note: you may find Allen-Bradley's document called *"1756 ControlLogix I/O Modules"* (publication 1756-TD002A-EN-E, May 2009) helpful in answering this question.

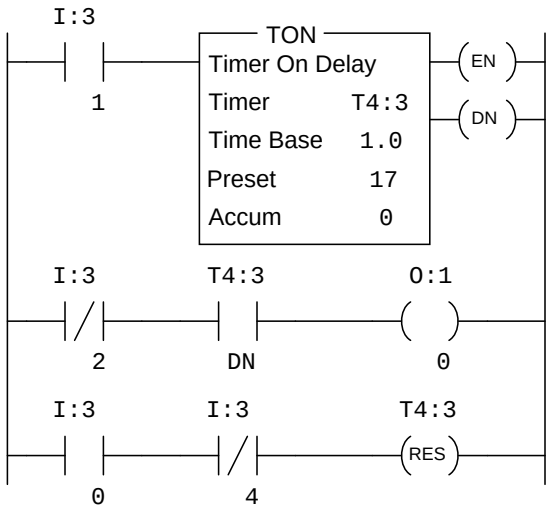
file i02039

Question 31

Suppose we have an Allen-Bradley model "SLC 500" PLC connected to switches and a pump contactor as shown in this illustration:



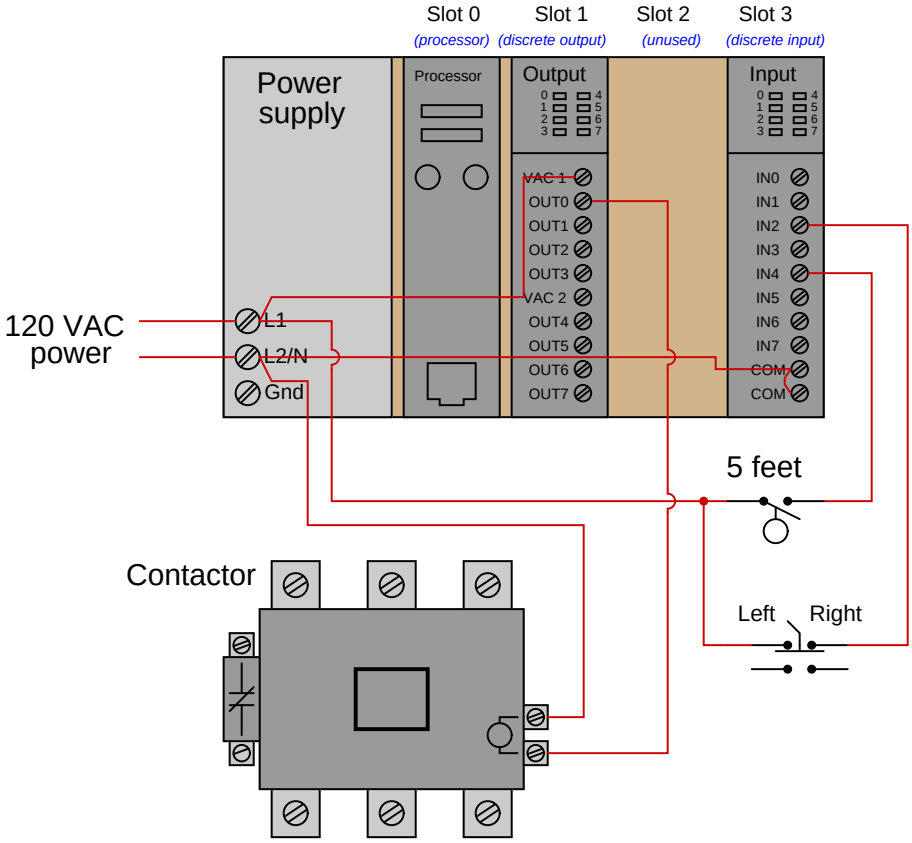
Identify the necessary conditions for the pump to turn on, based on this program running in the PLC:



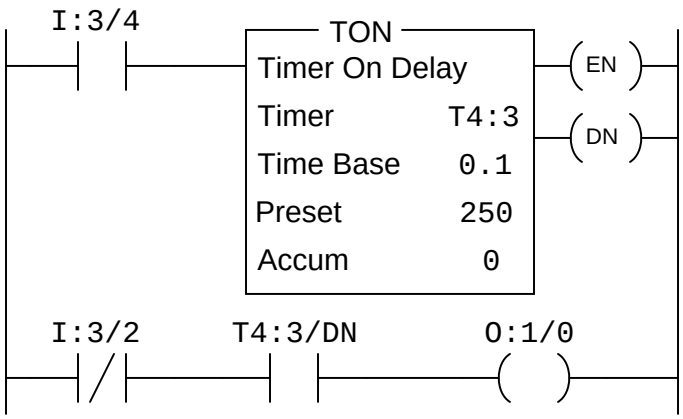
file i04635

Question 32

Suppose we have an Allen-Bradley model "SLC 500" PLC connected to a liquid level switch, a selector switch, and a motor contactor (for a pump) as shown in this illustration:



Explain what conditions must be met for the pump to turn on, based on an analysis of the program running in the PLC:



Suggestions for Socratic discussion

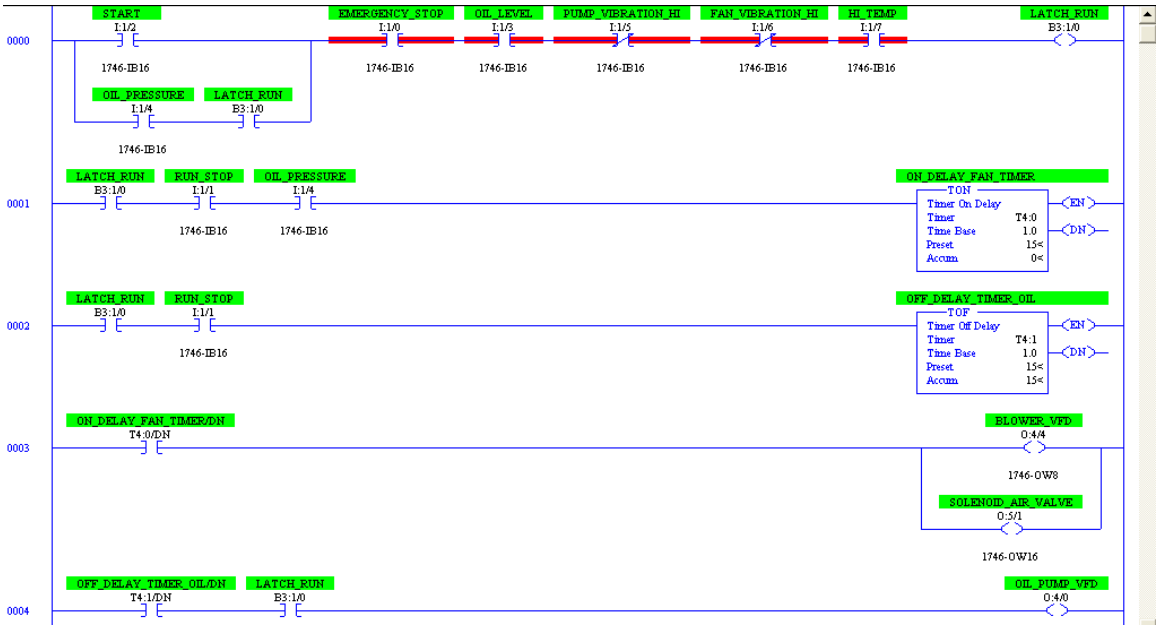
- What condition(s) will cause the "EN" bit in timer `T4:3` to activate?

- How will this system behave if the contactor coil fails open?
- How will this system behave if the contactor coil fails shorted?
- How will this system behave if the level switch fails open?
- How will this system behave if the wire connecting L1 to the VAC 1 terminal fails open?
- How will this system behave if the wire connecting L2/N to the COM terminals fails open?

file i04634

Question 33

An Allen-Bradley SLC 500 controls the start-up and shut-down of a large air blower (fan) with a pressurized lubrication oil sub-system to keep the blower bearings lubricated as they turn:



Analyze this control program, and then explain what each instruction does (including the practical function of each timer instruction). Also, identify all conditions that will shut down this system (stopping the blower motor and the oil pump).

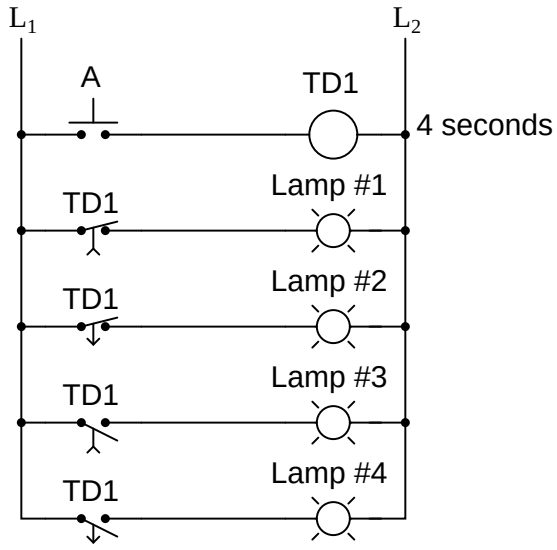
Suggestions for Socratic discussion

- Why is the oil pressure switch contact (`I:1/4`) in-line with the `LATCH_RUN` seal-in contact rather than being in-line with the other shut-down permissive contacts (oil level pump vibration, etc.)?
- Based on the color highlighting shown (red), what state is the program in?
- Identify all the "normal" electrical switch contact statuses for each shutdown switch (e.g. vibration, temperature, etc.) based on an examination of the contact instructions in this program.

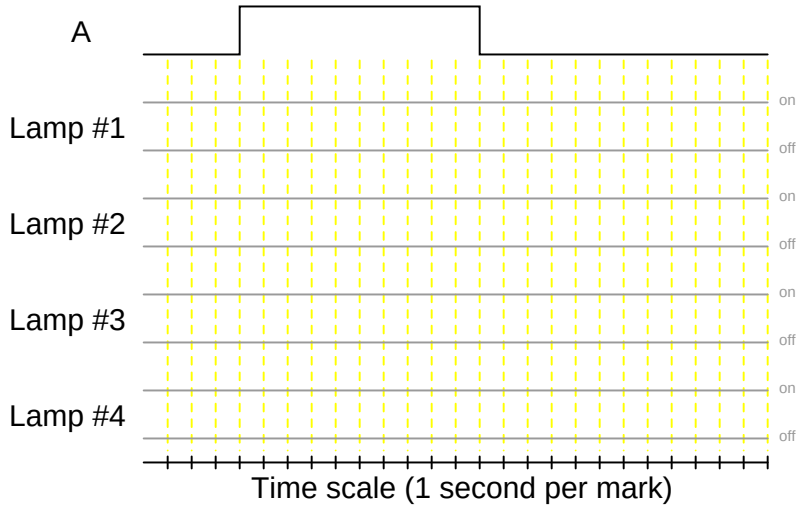
file i04592

Question 34

Time-delay relays are important circuit elements in many applications. Determine what each of the lamps will do in the following circuit when pushbutton "A" is pressed for 10 seconds and then released:



Show your answer by completing this timing diagram:



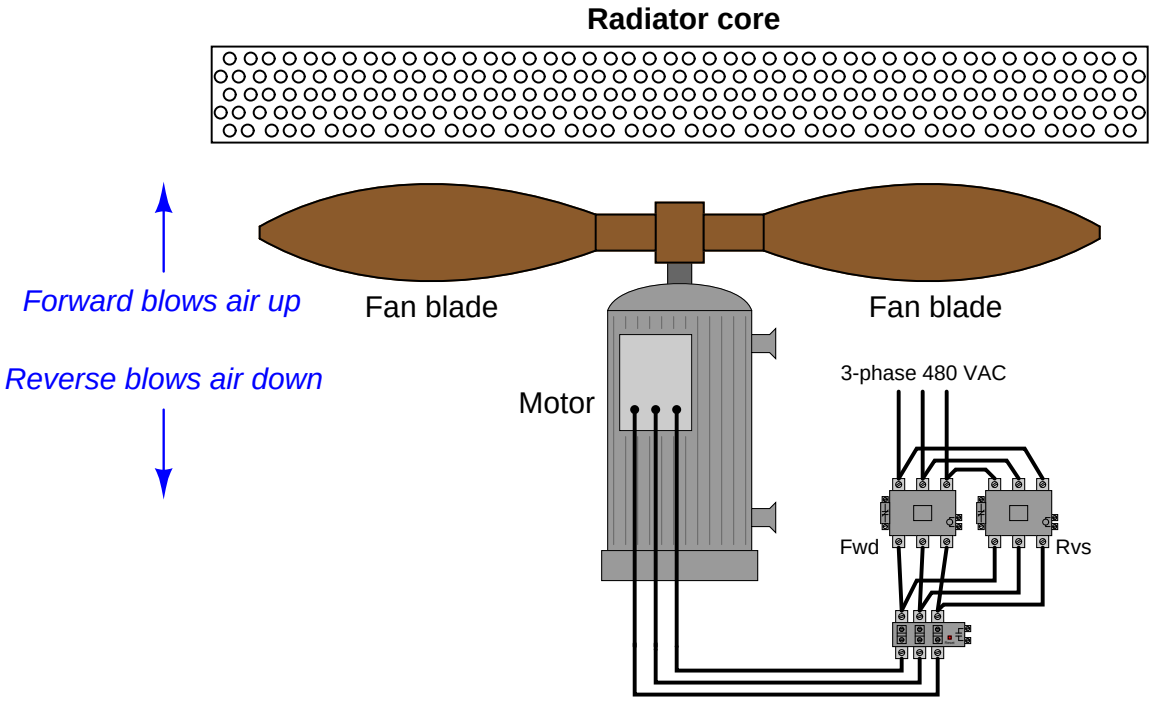
For each of the relay contacts shown in this circuit, identify whether it would be properly called an *on-delay* or an *off-delay* contact.

file i02500

Question 35

Programming Challenge – Reversing motor restart delay

A three-phase electric motor drives an air heat exchanger (radiative cooler) in either direction (forward or reverse), depending on which way operations personnel wish to blow the warm air. During warm weather, the preferred direction is up, to direct hot air away from process equipment. During cold weather, the preferred direction is down, to provide warmth in the process equipment area to help guard against liquid-filled pipes and tubes freezing:



A reversing start/stop PLC program is easy enough to write, with two momentary-contact "Start" pushbuttons (one for Forward, one for Reverse) and one momentary "Stop" pushbutton; but what we need here is a reversing program that *prevents an immediate re-start of the motor* in the opposite direction following a stop command. This is because the fan blades have a lot of inertia, and take about 30 seconds to coast to a stop. This restart lockout timer will prevent someone from trying to reverse the motor's direction before the fan has had a chance to fully stop.

Write a PLC program to provide this forward/reverse/restart lockout functionality. Assume the use of *normally-open* (NO) pushbutton switches for all pushbutton inputs.

Suggestions for Socratic discussion

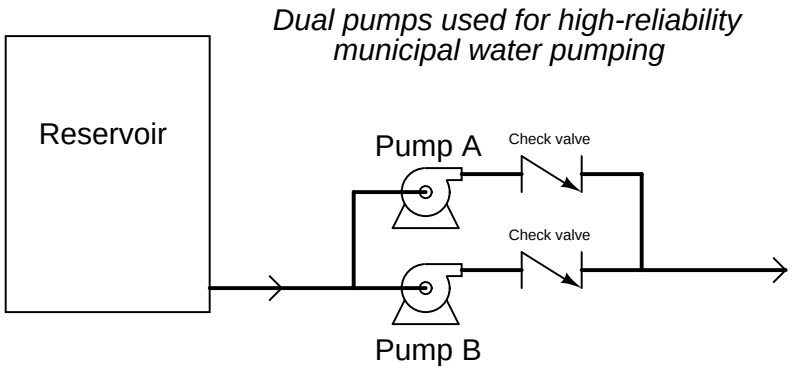
- What type of timer instruction is best suited for this application, an *on-delay* or an *off-delay* timer?

file i02347

Question 36

Programming Challenge – Run-time equalizing pump selection control

In critical process applications, it is common to find two or three pumps where a single pump would be sufficient for normal operation. Municipal water distribution and wastewater collection systems often use dual pumps for redundancy: one pump can take over for the other in the event of pump failure:



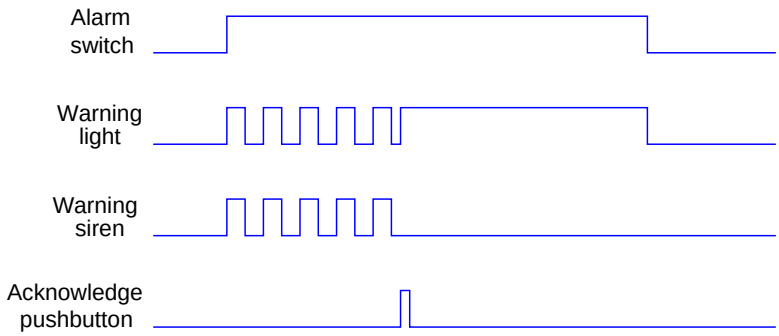
A potential problem with dual pumps is that the "spare" pump may suffer mechanical problems if it sits idle too long, and therefore will fail to perform its function as a "backup" unit should the primary pump fail for any reason. One solution to this problem is to choose the next pump to start based on which one has the least amount of accumulated run-time hours on it. Each time a pump starts, the pump to start is the one with the shortest run-time value.

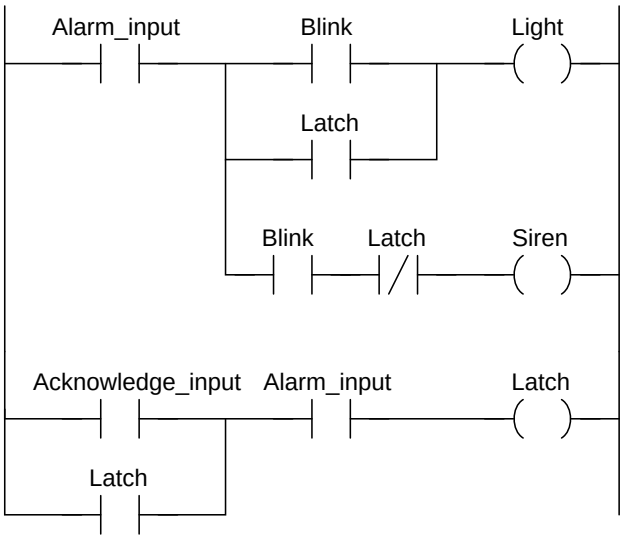
Write a PLC program to take "Start" and "Stop" pushbutton switch inputs and control two pumps in this fashion.

file i00126

Question 37

The following PLC program preforms the function of an *alarm annunciator*, where a discrete input signal from an alarm switch (e.g. high temperature alarm) first causes a warning light to blink and a siren to audibly pulse until a human operator presses an *acknowledge* pushbutton. If the alarm switch signal is still activated, the light will remain on (steady) instead of blink and the siren will go silent. The light turns off as soon as the alarm signal goes back to its "safe" state. A timing diagram shows how this should work:





Take this "generic" PLC program and enter it into your own PLC, assigning appropriate addresses to all instructions, and demonstrating its operation.

Suggestions for Socratic discussion

- Does the PLC program (as written) "expect" a *closed* alarm switch contact to trigger the alarm, or an *open* alarm switch contact?
- If the real-world alarm switch contact was a pressure switch wired NC (normally-closed), would this circuit function as a *low* pressure alarm or as a *high* pressure alarm?
- If the real-world alarm switch contact was a temperature switch wired NO (normally-open), would this circuit function as a *low* temperature alarm or as a *high* temperature alarm?

file i02342

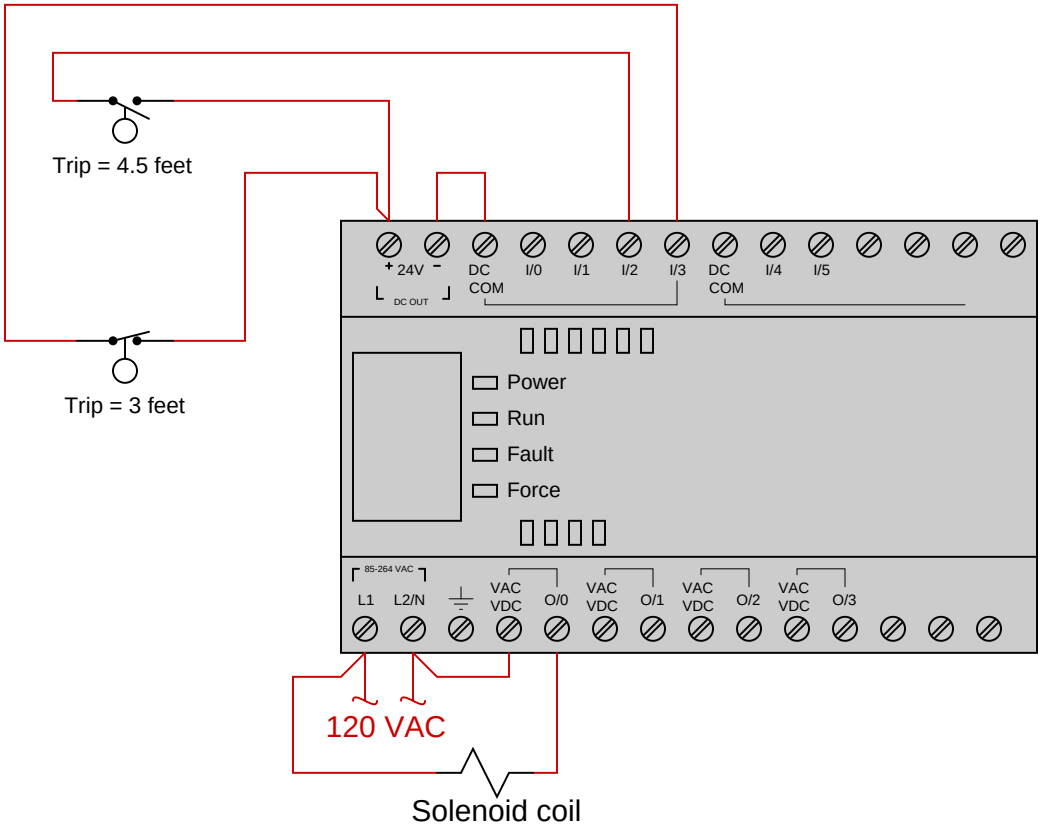
Question 38

Question 39

Question 40

Question 41

Suppose we have an Allen-Bradley MicroLogix 1000 PLC connected to two liquid level switches installed in the same tank, controlling a solenoid valve to empty liquid out of that tank:

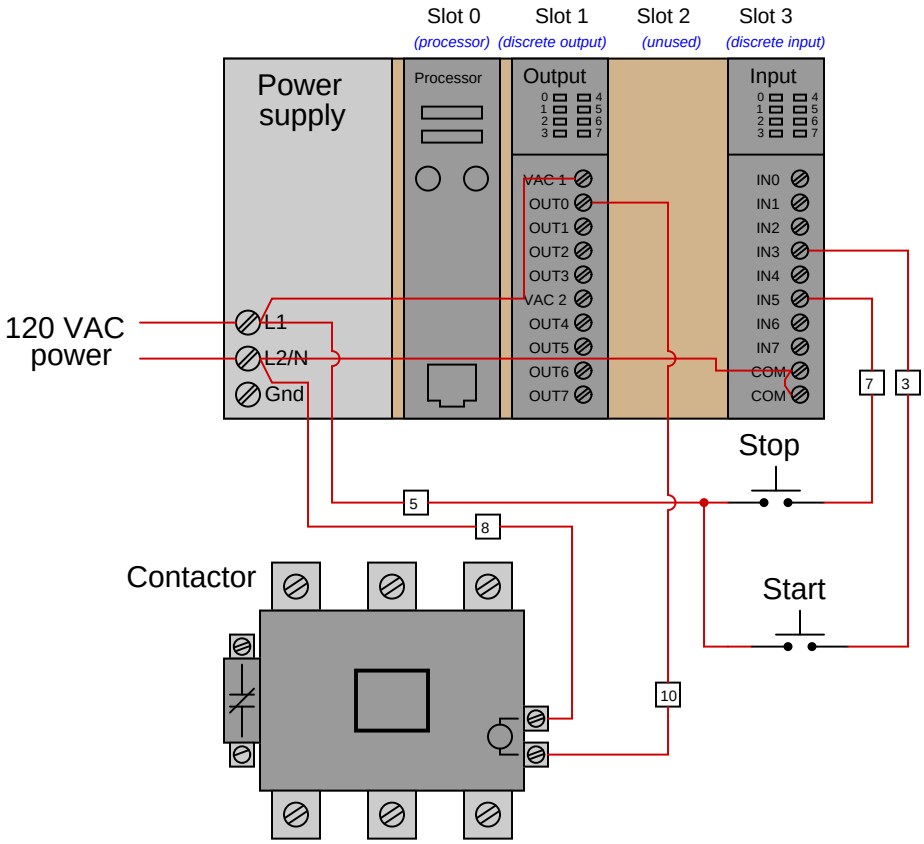


We wish for the solenoid valve to energize and open when the liquid level in the tank reaches 4.5 feet, then de-energize and shut when the liquid level falls to 3 feet. Write a RLL program for the PLC (complete with correct address labels for each of the virtual contacts) to fulfill this function:

file i02257

Question 42

Suppose the wire between terminal number 7 and input channel IN5 breaks open in this PLC-controlled motor starter system:

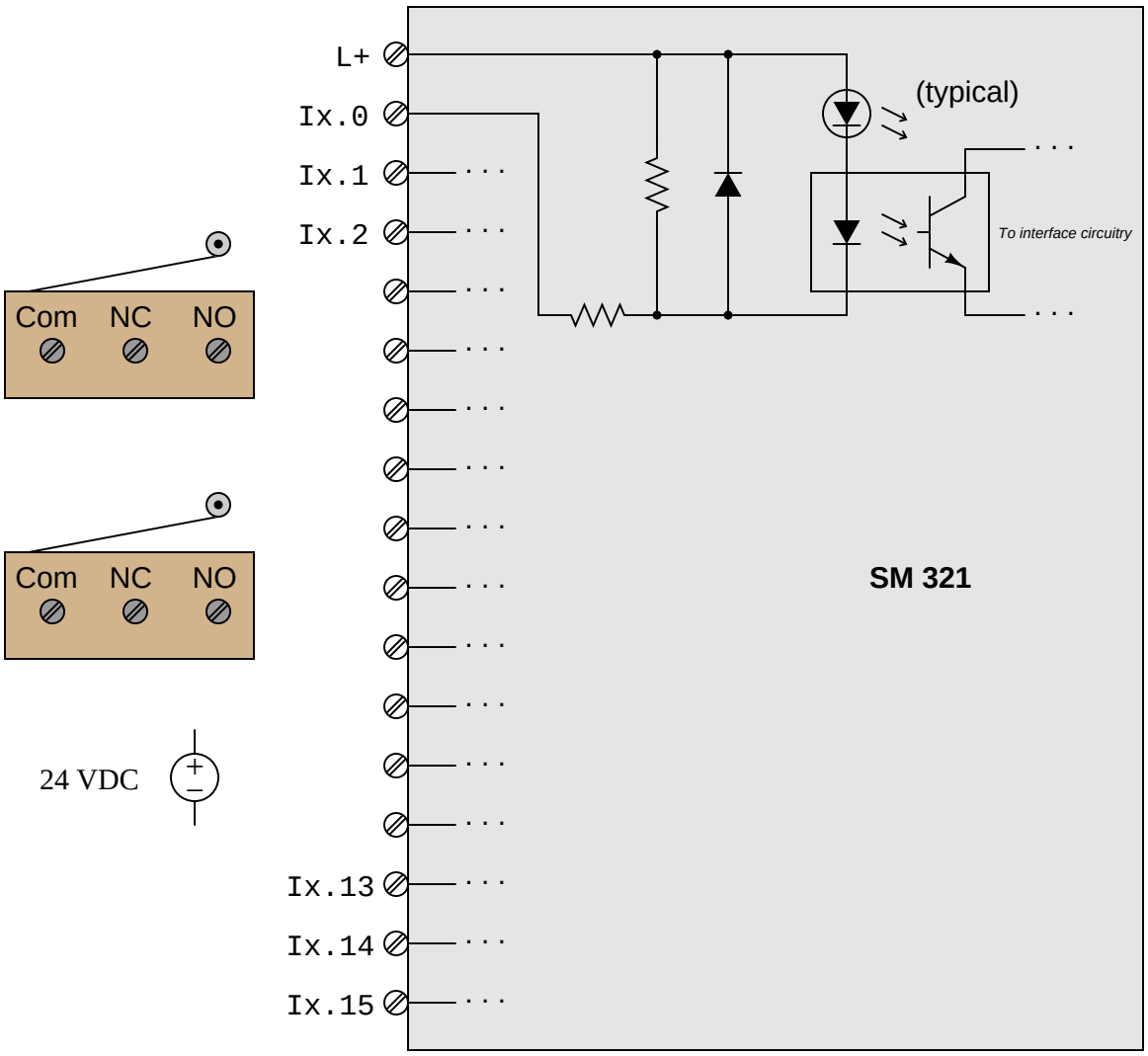


Determine the effect this fault will have on the system, and identify how that fault could be diagnosed using the color-highlighted RLL program display in the editing software of a personal computer connected to this PLC.

file i02378

Question 43

Sketch the wires necessary to connect two limit switches (normally-closed contacts) to input channels `Ix.5` and `Ix.11` of a Siemens SM 321 discrete input card (model 6ES7321-1BH50-0AA0). The internal schematic diagram of the first channel (`Ix.0`) is shown as "typical" for all the channels:



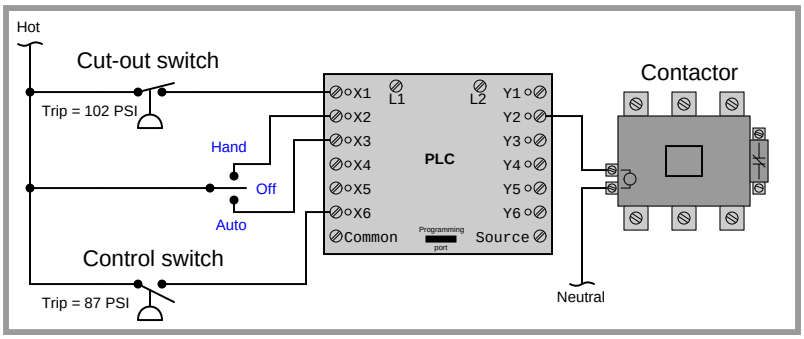
Also, identify whether this is a *sinking* or a *sourcing* input card, and sketch the directions of all currents through your sketched wires.

file i02508

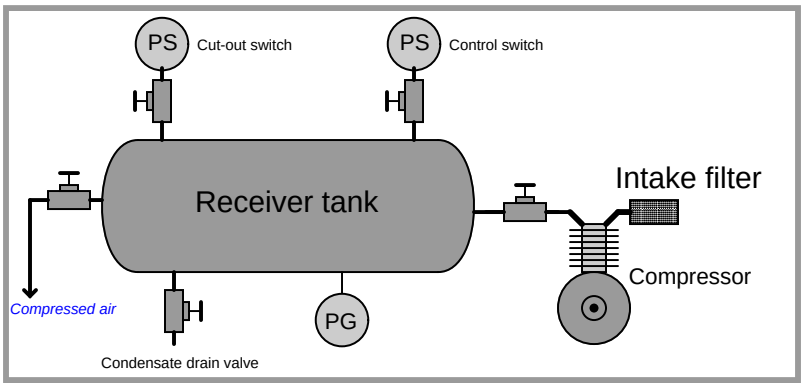
Question 44

A PLC is used to control the starting and stopping of an air compressor:

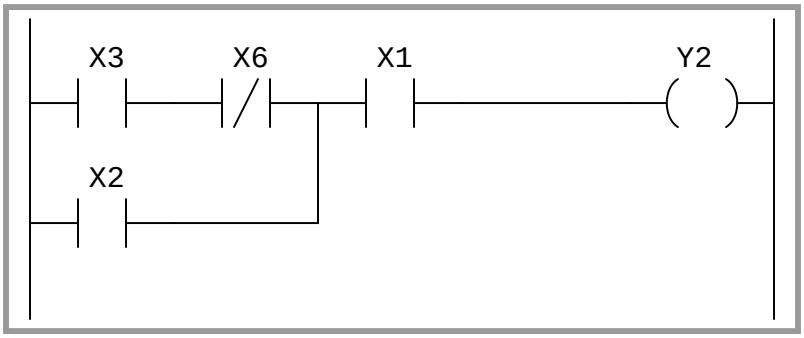
Control circuit schematic



Pictorial diagram of system



Relay Ladder Diagram program in PLC

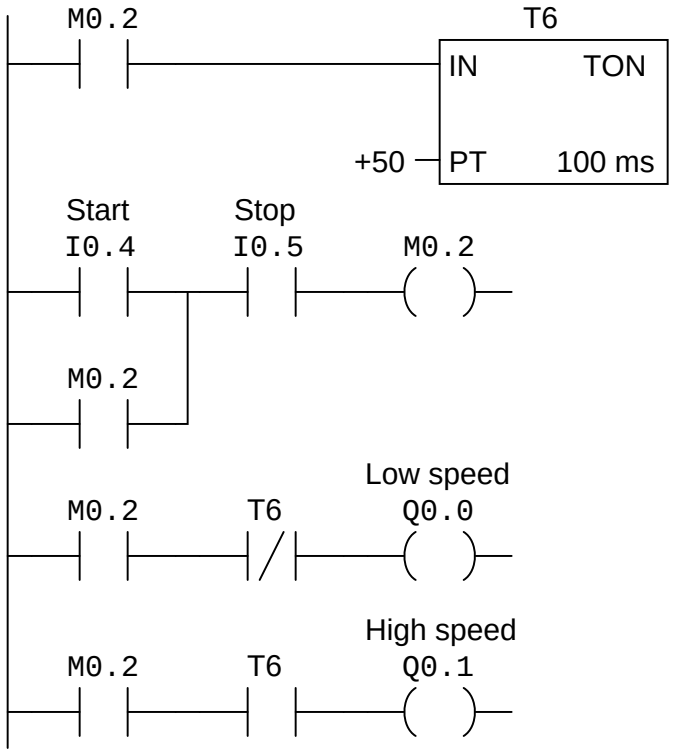


Suppose the electrical contact on the control switch (trip pressure = 87 PSI) corrodes, such that it cannot form a good connection when it's supposed to close. Explain how this will affect the operation of this system, and also how you could diagnose the problem by viewing the indicator LEDs on the PLC, as well as by monitoring the "live" contact status in the Ladder Diagram with a laptop computer.

file i02256

Question 45

Analyze this Siemens S7-200 PLC program (for controlling a motor) and explain what it is supposed to do:

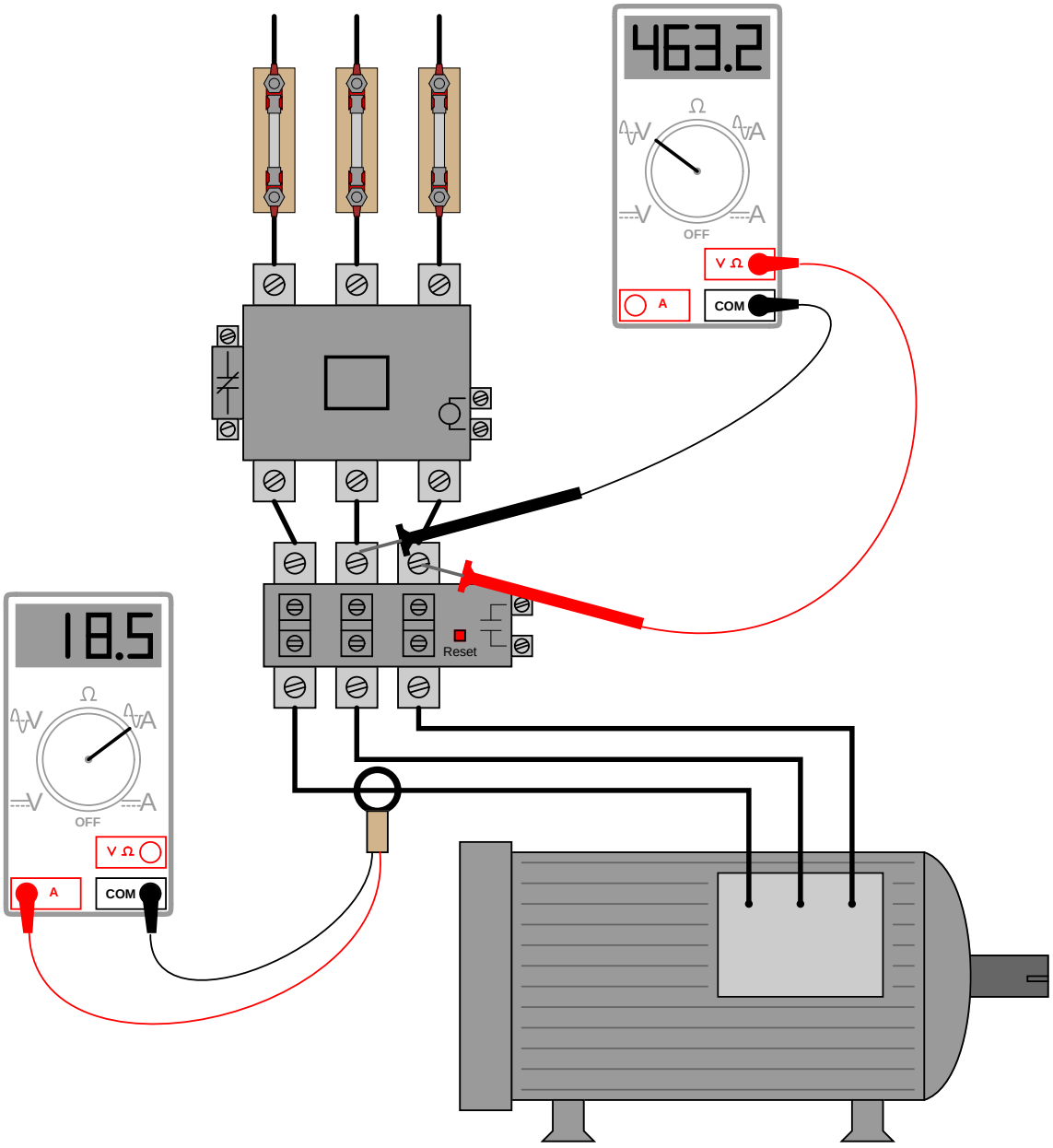


Include an explanation of the motor contactor wiring, based on an analysis of the PLC program.

file i02255

Question 46

Suppose a technician connects a voltmeter and an ammeter to the three-phase conductors of an running electric motor as shown in this simplified illustration (all control wiring has been omitted for simplicity):

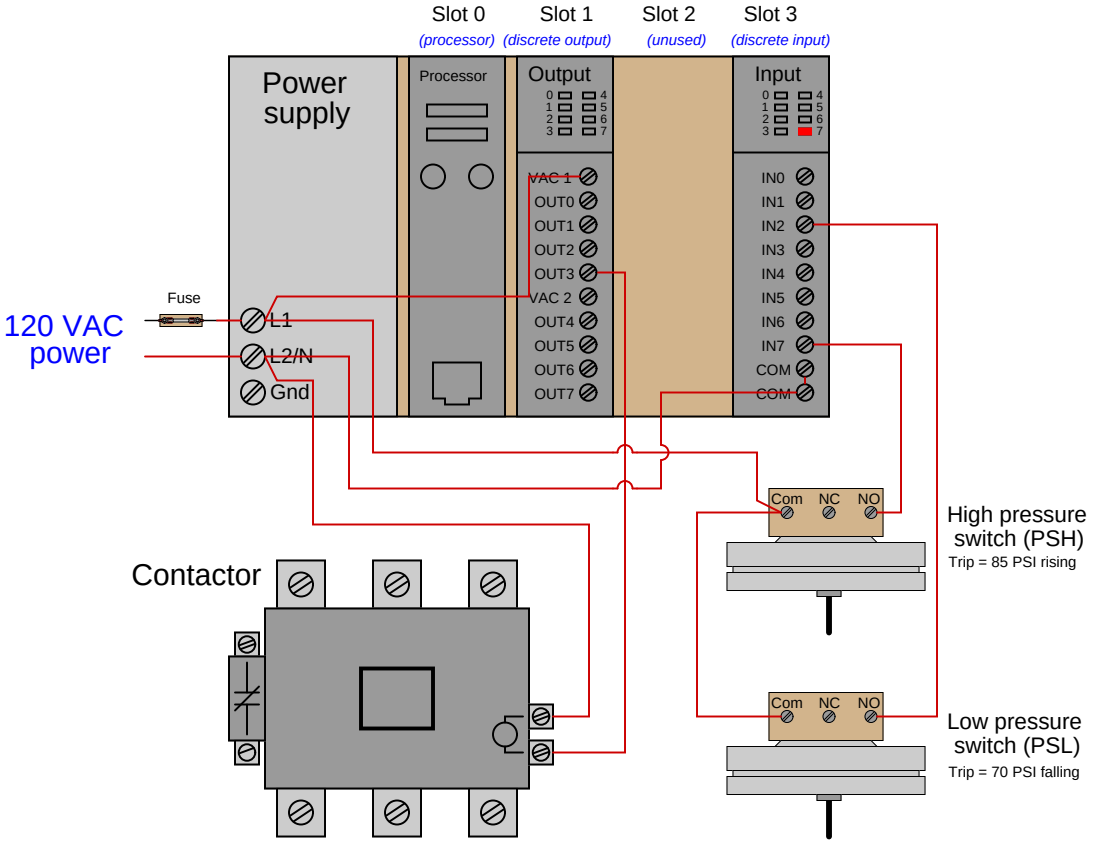


Calculate the mechanical horsepower output of this motor, assuming 91% efficiency and perfect power factor.

file i02258

Question 47

An Allen-Bradley SLC 500 PLC is used to control an air compressor, using an across-the-line motor starter. All 480 volt power wiring has been omitted for simplicity:



The system is broken, though: the compressor refuses to start even though the air tank is empty (no air pressure). You have no test equipment with you – all you have is what you see in the above illustration.

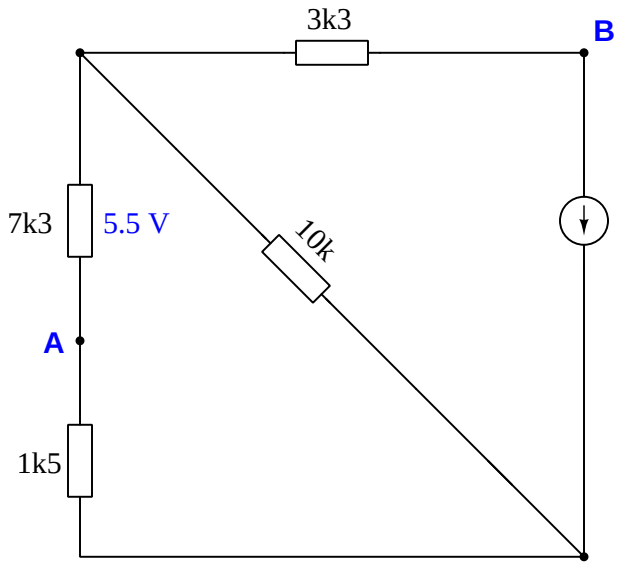
Identify the likelihood of each specified fault in this system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* observations and symptoms in this circuit.

Fault	Possible	Impossible
Open wire between PSL and IN2 terminal		
Open wire between PSH and IN7 terminal		
Open contactor coil		
Shorted contactor coil		
PSL stuck (as though $P > 70$ PSI)		
PSH stuck (as though $P > 85$ PSI)		
Failed input card		
Failed output card		
PLC program halted		
Blown fuse		

file i02254

Question 48

Determine all component voltages and currents in this circuit, being sure to mark directions of all currents (conventional flow notation) and polarities of all voltages:

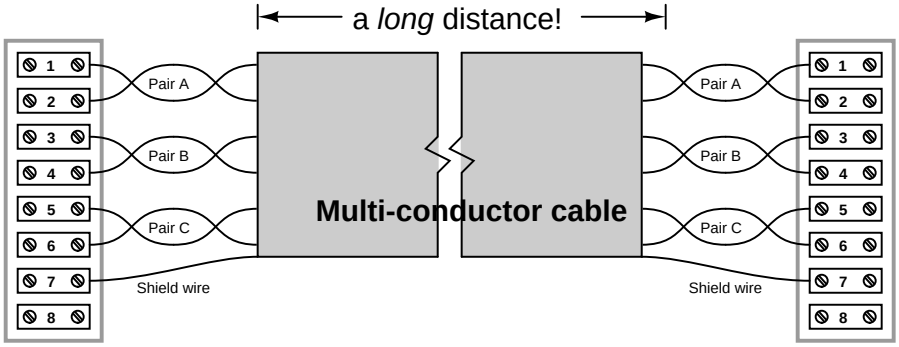


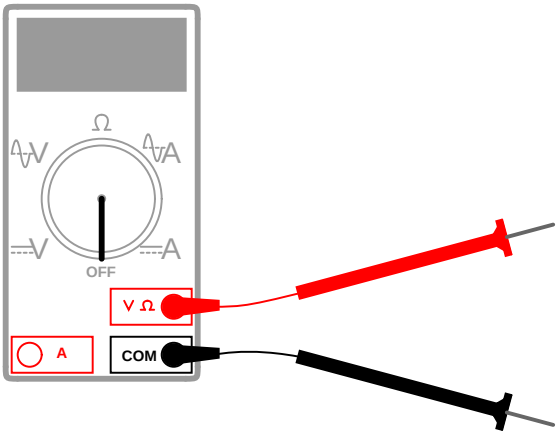
Also, identify the amount of voltage between points A and B.

file i02272

Question 49

Suppose a technician needs to test a pair of wires in a newly-installed multi-pair cable for open and short faults. The cable ends are terminated at terminal blocks too far away to permit a multimeter's test leads to stretch from one end to the other:





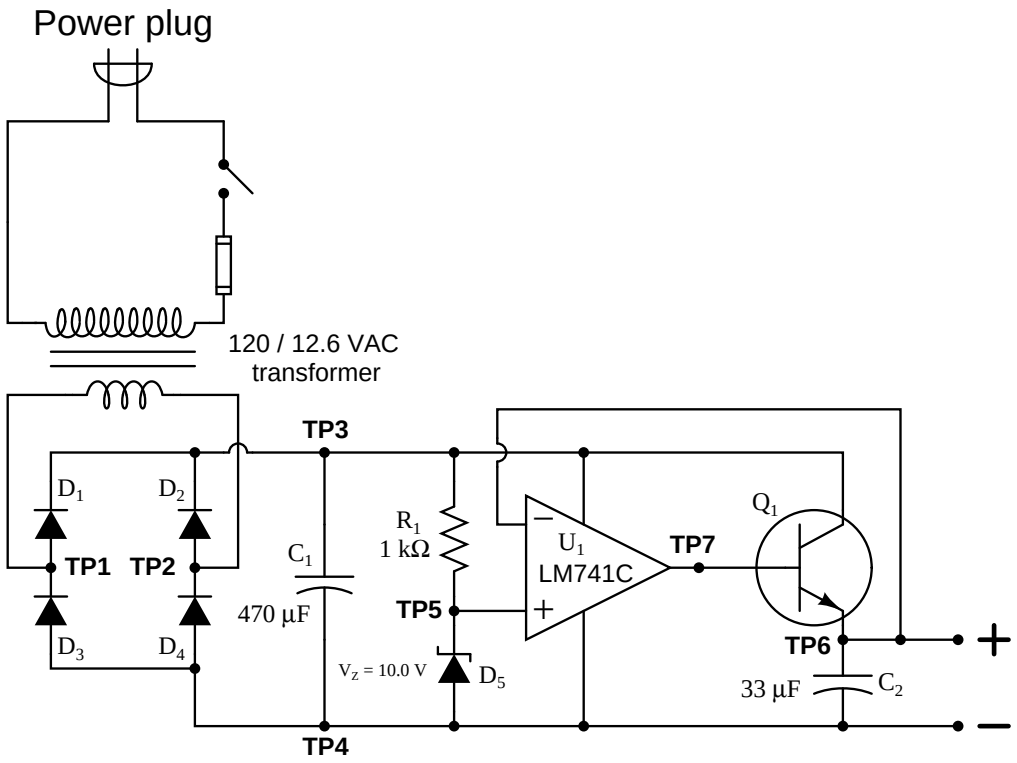
Devise a series of measurements that a technician could take using a multimeter located at one end of the cable. Be sure to specify which setting the multimeter should be configured for, and which terminals the test leads should touch. Also, be sure to specify what range of measurements would indicate "good" versus "bad" for each test:

- Pair "A" wires shorted together in cable
- Either conductor of Pair "A" being broken (open)
- Either conductor of Pair "A" shorted to cable shield

file i02263

Question 50

Something is wrong with this regulated DC power supply circuit. The output is supposed to be +10.0 volts, but instead it measures only about 1 volt:



Using your digital multimeter, you measure 10.0 volts between test points TP5 (red test lead) and TP4 (black test lead). From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted) other than the 120 volt AC power source, on/off switch, and fuse. The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted

1.
2.

- Circuit elements that must be functioning properly

1.
2.

file i03190

Question 51

Lab Exercise – introduction

Your team's task is to construct a system controlled by a PLC. The system you choose to build shall use (at minimum) discrete input(s), discrete output(s), and either counter or timer functions. This system will be expanded during the next course to include a three-pole contactor, so designing the system with this in mind (or simply installing the contactor in this exercise) will save you time later. Project ideas include:

- Air compressor control, with high and low air pressure switches
- Water sump pump control, with high and low water level switches
- Other alternatives? *Must be pre-approved by instructor!*

In addition to functioning properly, the PLC program must be *fully* documented and edited for cleanliness and good programming form. This includes labels (aliases, or symbolic names) for all inputs and outputs, and comments for each and every rung of logic explaining the rungs' functions. Although there will be only one program submitted by each team, completion of this objective is individual, with each student explaining (at least) a part of the PLC program to the instructor.

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch (do *first!*)	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Complete I/O list	mastery	–	–	–	–	
Prototype PLC program (*before programming!*)	mastery	–	–	–	–	
Final wiring diagram and system inspection	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Final PLC program inspection	mastery					– – – –
Lab question: Wiring connections	proportional					– – – –
Lab question: Commissioning	proportional					– – – –
Lab question: Mental math	proportional					– – – –
Lab question: Diagnostics	proportional					– – – –

The only "proportional" scoring in this activity are the lab questions, which are answered by each student individually. A listing of potential lab questions are shown at the end of this worksheet question. The lab questions are intended to guide your labwork as much as they are intended to measure your comprehension, and as such the instructor may ask these questions of your team day by day, rather than all at once (on a single day).

It is essential that your team plans ahead what to accomplish each day. A short (10 minute) team meeting at the beginning of each lab session is a good way to do this, reviewing what's already been done, what's left to do, and what assessments you should be ready for. There is a lot of work involved with building, documenting, and troubleshooting these working instrument systems!

As you and your team work on this system, you will invariably encounter problems. You should always attempt to solve these problems as a team before requesting instructor assistance. If you still require instructor assistance, write your team's color on the lab whiteboard with a brief description of what you need help on. The instructor will meet with each team in order they appear on the whiteboard to address these problems.

Lab Exercise – team meeting and prototype sketch

An important first step in completing this lab exercise is to **meet with your instructor** as a team to discuss safety concerns, team performance, and specific roles for team members. If you would like to emphasize exposure to certain equipment (e.g. use a particular type of control system, certain power tools), techniques (e.g. fabrication), or tasks to improve your skill set, this is the time to make requests of your team so that your learning during this project will be maximized.

An absolutely essential step in completing this lab exercise is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This usually takes the form of a simple electrical schematic and/or loop diagram showing all electrical connections between components, as well as any tubing or piping for fluids. This prototype sketch need not be exhaustive in detail, but it does need to show enough detail for the instructor to determine if all components will be correctly connected for their safe function.

For example, if you intend to connect field devices to a PLC (Programmable Logic Controller), your prototype sketch must show how those devices will connect to typical input/output terminals on the PLC, where electrical power will be supplied, etc. Prototype sketches need not show all intermediary connections between components, such as terminal blocks in junction boxes between the field device and the controller.

You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of electric current, voltage polarities, and identifying electrical sources/loads. Use this task as an opportunity to strengthen your analytical skills! Remember that you will be challenged in this program to do all of this on your own (during "capstone" assessments), so do not make the mistake of relying on your teammates to figure this out for you – instead, treat this as a problem *you* must solve and compare your results with those of your teammates.

Your team's prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team's working system begins. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* Similarly, you should not deviate from the prototype design without instructor approval, to ensure nothing will be done to harm equipment by way of incorrect connections. Each member on the team should have ready access to this plan (ideally possessing their own copy of the plan) throughout the construction process. Prototype design sketching is a skill and a habit you should cultivate in school and take with you in your new career.

Select a PLC with modular (add-on) I/O cards to provide sufficient complexity for the project. Monolithic "brick" PLCs (with no add-on I/O modules) are not acceptable for this project. An Allen-Bradley SLC 500 PLC would be a good choice, as well as a Siemens S7 series or an AutomationDirect Productivity 3000.

You will also need to select appropriate field devices (switches, pumps, etc.) for your project. You are free to use the field devices left over from the relay-based motor control lab if you prefer.

The next step should be finding appropriate documentation for your PLC. All PLC manufacturers provide manuals and datasheets for their products online. Use this documentation to identify how to properly wire, power, and program your team's PLC.

PLC equipment manuals always provide sample diagrams showing how external components may connect to the I/O points. Feel free to use these sample diagrams as templates for your prototype sketch. *This is the most challenging portion of your wiring, so be sure to work with your teammates to get this right!*

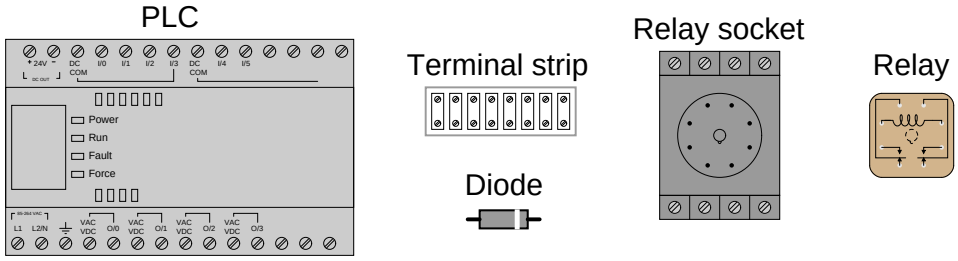
Planning a functioning system should take no more than a couple of hours if the team is working efficiently, and will save you hours of frustration (and possible component destruction!).

Lab Exercise – circuit design challenge

Connect an "ice cube" relay to one of the outputs on a PLC, so that the PLC can control the energization of the relay. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, or "alligator" clips permitted). Program this PLC to implement a motor start/stop (latching) control function. *In order to ensure your program has not been pre-written in your computer prior to this assessment, you will be asked to sketch a correct ladder-diagram PLC program on paper to implement this function prior to using a computer.*

You must connect a "commutating" diode in parallel with the relay's coil to prevent the phenomenon known as "inductive kickback," which may otherwise damage the transistor output on a PLC. Note that incorrectly connecting this diode will present a short-circuit to the PLC, so you *must* get it right!

This exercise tests your ability to properly interpret the "pinout" of an electromechanical relay, properly wire a PLC output channel to control a relay's coil, properly polarize a commutating diode to prevent inductive kickback from damaging the PLC output, and use a terminal strip to organize all electrical connections. It also tests your ability to program motor start/stop logic using either a seal-in contact or latching (retentive) coil instructions.



The following components and materials will be available to you: assorted "ice cube" **relays** with DC-rated coils and matching **sockets** ; **terminal strips** ; 1N400X rectifying **diodes** ; lengths of **hook-up wire**. You will be expected to supply your own screwdrivers and multimeter for assembling and testing the circuit at your desk.

"Start" switch to input: ____ **"Stop" switch to input**: ____ **Relay to output**: ____

PLC program (instructor chooses): ____ Seal-in contact ____ Retentive coils

Lab Exercise – developing a PLC I/O list

It is a good idea when programming any computer system to first identify all the input and output signals to the system, as well as internal variables if possible, before commencing on the development of the program itself. In order to reinforce this practice, your team will be required to develop a complete list of all input and output points on your proposed system along with any tagnames (also known as "symbols" or "nicknames") identifying the function of each.

Once this list is complete and you are ready to begin developing the PLC program, you can enter all the tagnames and define the I/O points as your very first programming step. With this data in place, the writing of your program will be made easier because each I/O tag you reference will already be defined and labeled, reminding you of their functions within the system.

Here is a sample I/O list for a motor control PLC program:

Hardware I/O terminal	I/O type	Tagname	Notes
Card 1, terminal IN0	24 VDC discrete input	START_PB	Black pushbutton, momentary NO contacts
Card 1, terminal IN1	24 VDC discrete input	STOP_PB	Red pushbutton, momentary NC contacts
Card 1, terminal IN2	24 VDC discrete input	E_STOP	Red pushbutton, latching NC contacts
Card 2, terminal IN0	4-20 mA analog input	MTR_TEMP	Current signal scaled 0 to 150 deg F
Card 3, terminal OUT0	120 VAC discrete output	CONTACTOR	To terminal A1

Lab Exercise – wiring the system

The Instrumentation lab is set up to facilitate the construction of working systems, with over a dozen junction boxes, pre-pulled signal cables, and "racks" set up with 2-inch vertical pipes for mounting instruments. The only wires you should need to install to build a working system are those connecting the field instrument to the nearest junction box, and then small "jumper" cables connecting different pre-installed cables together within intermediate junction boxes.

Your team's PLC must be installed in a suitable electrical enclosure, with AC power fed to it through a fuse or circuit breaker (on the "hot" conductor only), and firmly grounded (the ground conductor of the power cord securely fastened to the metal frame of the enclosure and the PLC chassis).

All I/O wiring should be neatly loomed together and/or run through wire duct ("Panduit"). Power to I/O cards must be routed through their own fuses so that I/O power may be disconnected independently of power to the PLC processor and rack.

Common mistakes:

- Neglecting to consult the manufacturer's documentation for field instruments (e.g. how to wire them, how to calibrate them).
- Proceeding with wiring *before* creating an initial sketch of the circuitry and checking that sketch for errors.
- Mounting the field instrument(s) in awkward positions, making it difficult to reach connection terminals or to remove covers when installed.
- Failing to tug on each and every wire where it terminates to ensure a mechanically sound connection.
- Students working on portions of the system in isolation, not sharing with their teammates what they did and how. It is important that the whole team learns all aspects of their system!

Building a functioning system should take no more than one full lab session (3 hours) if all components are readily available and the team is working efficiently!

Lab Exercise – programming the system

Like wiring a control system, programming one is best done with thoughtful planning rather than a "design-as-you-build" approach. Each team will work with the instructor to develop a "prototype" PLC program, usually on a whiteboard or on paper. *Having multiple teams prototype their programs on whiteboards within the same classroom works well to foster peer review of programming, where teams analyze and critique other teams' programming solutions!* Your prototype program should completely address the following points:

- Identify all inputs to the PLC, giving each one a sensible tagname
- Identify all signal outputs from the PLC, giving each one a sensible tagname
- Identify all major program functions (i.e. *What must this program do?*)
- Identify all internal variables necessary for these functions, giving each one a sensible tagname
- Identify all system variables necessary for these functions (e.g. real-time clock/calendar variables)

The importance of identifying and naming all relevant variables is paramount to "clean" programming. This is especially true when an HMI (Human-Machine Interface) is to be connected to the PLC, and all relevant variables must be named there as well.

A reasonable approach to developing a robust program prototype is to create your prototype in your own personal ("brick") PLC, de-bugging it there with all the switches in place to simulate input signals. Even if your personal PLC is a different model (or manufacture) than the project PLC, this is a very helpful exercise. Furthermore, it allows you to continue program development outside of school when you do not have access to the project PLC.

Only after a prototype program is developed should you begin programming the project PLC. I recommend the following steps:

- Establish communications between PLC and personal computer (PC)
- Connect all I/O cards (modules) to the PLC and get them recognized by the processor
- Assign tagnames to all relevant variables, beginning with I/O points
- Enter a simplified version of the program, running to check for "bugs"
- Diagnose any program problems
- Add complexity to the program (e.g. additional features) and run to check for "bugs"
- Repeat last two steps as often as necessary
- Add comments to each and every line of the program, explaining how it functions

The final program should be well-documented, clean, and as simple as possible. All members of the team should have a hand in designing the program, and everyone *must* thoroughly understand how it works.

Common mistakes:

- Waiting too long after writing the program code to insert comments. This is best done immediately, while everything makes sense and is fresh in your memory!
- Insufficient commenting – only makes sense to the person who did the programming
- Students working on portions of the program in isolation, not sharing with their teammates what they did and how. It is important that the whole team learns all aspects of their system!

Lab Exercise – documenting the system

Each student must sketch their own *wiring diagram* for their team's system, following industry-standard conventions. Sample diagrams for input and output wiring are shown in the next question in this worksheet. These wiring diagrams must be *comprehensive* and *detailed*, showing every connection, every cable, every terminal block, etc. The principle to keep in mind here is to make the wiring diagram so complete and unambiguous that anyone can follow it to see what connects to what, even someone unfamiliar with industrial instrumentation. In industry, control systems are often constructed by contract personnel with limited understanding of how the system is supposed to function. The associated diagrams they follow must be so complete that they will be able to connect everything properly without necessarily understanding how it is supposed to work.

When your entire team is finished drafting your individual wiring diagrams, call the instructor to do an inspection of the system. Here, the instructor will have students take turns going through the entire system, with the other students checking their diagrams for errors and omissions along the way. During this time the instructor will also inspect the quality of the installation, identifying problems such as frayed wires, improperly crimped terminals, poor cable routing, missing labels, lack of wire duct covers, etc. The team must correct all identified errors in order to receive credit for their system.

After successfully passing the inspection, each team member needs to place their wiring diagram in the diagram holder located in the middle of the lab behind the main control panel. When it comes time to troubleshoot another team's system, this is where you will go to find a wiring diagram for that system!

Common mistakes:

- Forgetting to label all signal wires (see example wiring diagrams).
- Forgetting to label all field instruments with their own tag names (e.g. PSL-83).
- Forgetting to note all wire colors.
- Forgetting to put your name on the wiring diagram!
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.

Creating and inspecting accurate wiring diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

Lab questions

- **Wiring connections**
- Determine correct wire connections between field components and a PLC I/O card to create a working PLC input or output circuit, based on diagrams of components with terminals labeled
- Correctly determine all electrical sources and loads, as well as all voltage polarities and current directions, in a DC input or output circuit, based on diagrams of field components and the PLC's I/O card with terminals labeled

- **Commissioning and Documentation**
- Explain what is meant by the term "sinking" with regard to a PLC input card (DC)
- Explain what is meant by the term "sourcing" with regard to a PLC input card (DC)
- Explain what is meant by the term "sinking" with regard to a PLC output card (DC)
- Explain what is meant by the term "sourcing" with regard to a PLC output card (DC)
- Explain what a "TRIAC" PLC output card is, and how it differs from DC output cards
- Explain what a "relay" PLC output card is, and how it differs from sourcing or sinking DC output cards
- Explain the distinction between "online" and "offline" programming modes for a PLC

- **Mental math** (no calculator allowed!)
- Convert a binary number into decimal
- Convert a binary number into hexadecimal
- Convert a decimal number into binary
- Convert a hexadecimal number into binary
- Convert a hexadecimal number into decimal

- **Diagnostics**
- Examine a PLC program and identify any mistakes in it
- Determine whether or not a given diagnostic test will provide useful information, given a set of symptoms exhibited by a failed system
- Identify at least two plausible faults given the results of a diagnostic test and a set of symptoms exhibited by a failed system
- Propose a diagnostic test for troubleshooting a failed system and then explain the meanings of two different test results

Wiring diagram requirements

- **Wiring diagram**
- Proper symbols and designations used for all components.
- Relay coil and contacts properly named.

- **Text descriptions**
- Each instrument documented below (tag number, description, etc.).
- Calibration (input and output ranges) given for each instrument, as applicable.

- **Connection points**
- All terminal blocks properly labeled.
- All terminals shown in proper order on diagram.
- All I/O cards and points fully labeled (complete with program addresses).
- All wires are numbered.
- All electrically-common points in the circuit shall bear the same wire number.
- All wire colors shown next to each terminal.

- **Cables and tubes**
- Multi-pair cables or pneumatic tube bundles going between junction boxes and/or panels need to have unique numbers (e.g. "Cable 10") as well as numbers for each pair (e.g. "Pair 1," "Pair 2," etc.).

- **Energy sources**
- All power source intensities labeled (e.g. "24 VDC," "120 VAC," "20 PSI")
- All shutoff points labeled (e.g. "Breaker #5," "Valve #7")

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Question 52

Wiring diagram requirements

Perhaps the most important rule to follow when drafting a wiring diagram is *your diagram should be complete and detailed enough that even someone who is not a technician could understand where every wire should connect in the system!*

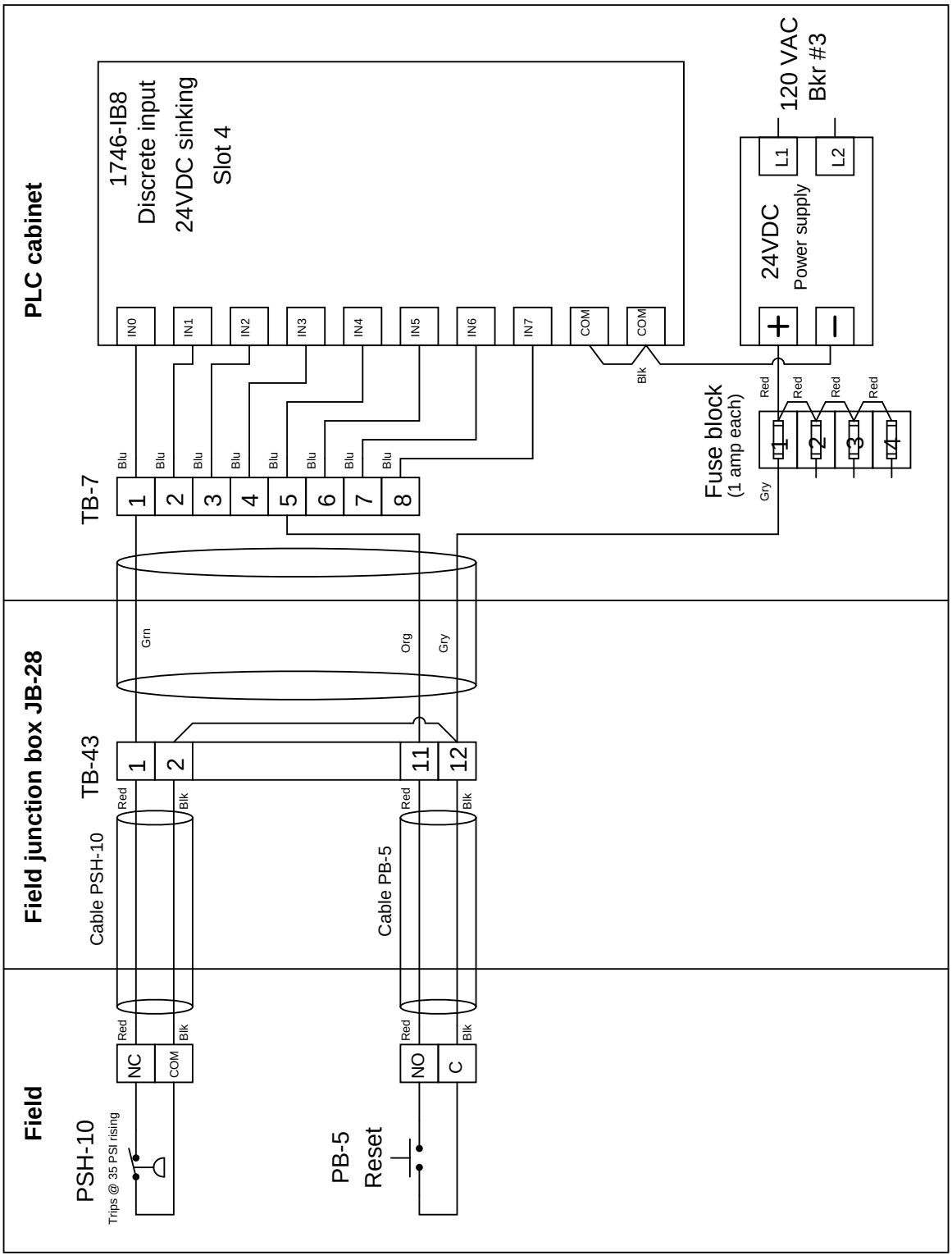
- **Field device symbols**
- Proper electrical symbols and designations used for all field devices.
- *Optional:* Trip settings written next to each process switch.

- **PLC I/O cards**
- All terminals labeled, even if unused in your system.
- Model number, I/O type, and PLC slot number should be shown for each and every card.

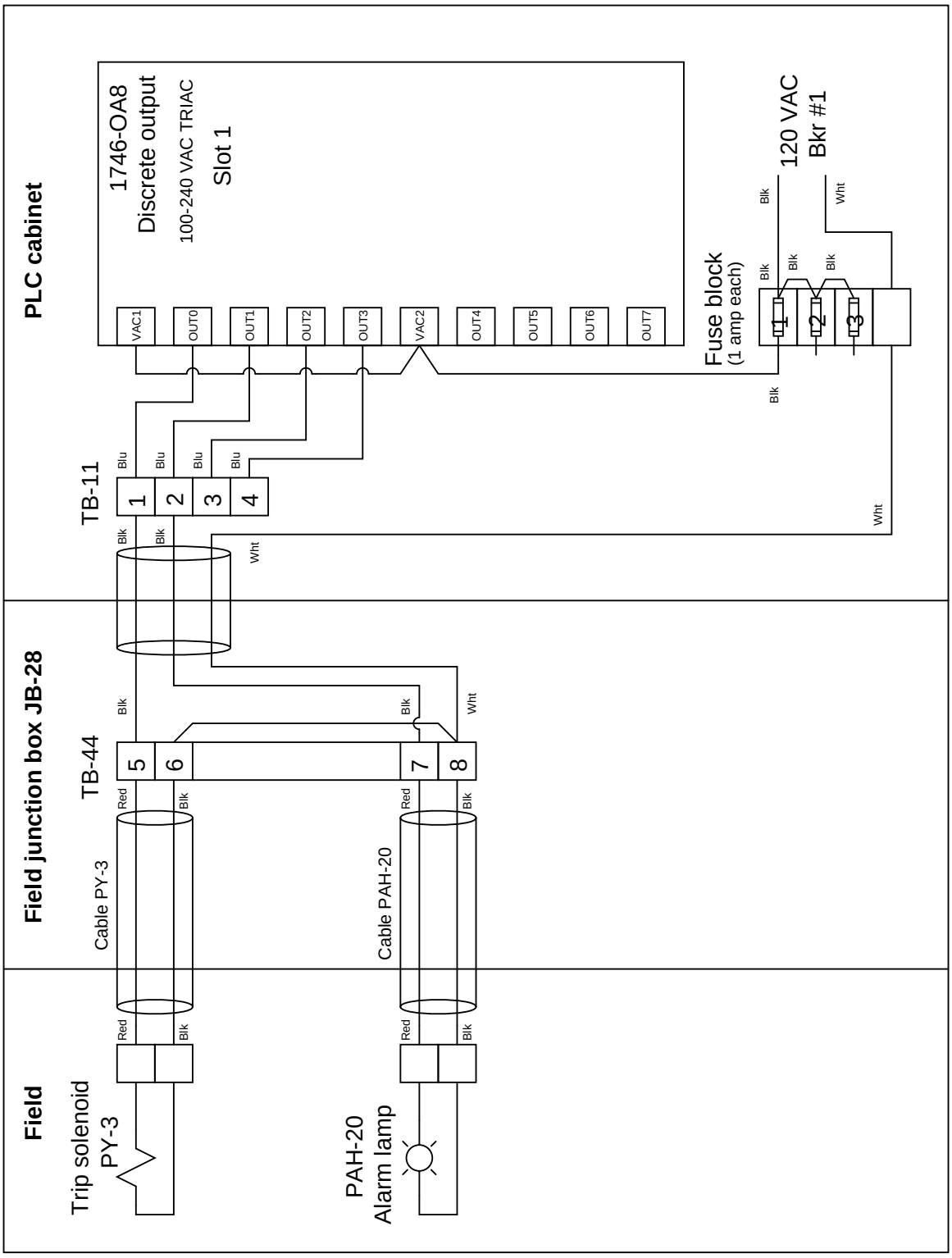
- **Connection points**
- All terminals properly labeled.
- All terminal blocks properly labeled.
- All junction ("field") boxes shown as distinct sections of the loop diagram, and properly labeled.
- All control panels shown as distinct sections of the loop diagram, and properly labeled.
- All wire colors shown next to each terminal.
- All terminals on devices labeled as they appear on the device (so that anyone reading the diagram will know which device terminal each wire goes to).

- **Energy sources**
- All power source intensities labeled (e.g. "24 VDC," "120 VAC," "480 VAC 3-phase")
- All shutoff points labeled (e.g. "Breaker #5," "Valve #7")

Sample Input Wiring Diagram



Sample Output Wiring Diagram



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Answers

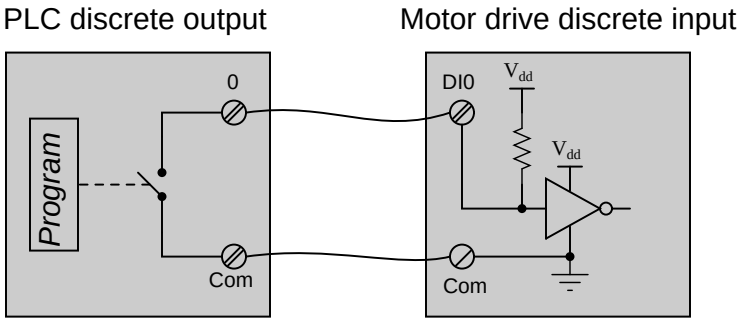
Answer 1

Answer 2

Answer 3

Answer 4

Here is a schematic diagram to help you formulate an answer:



Answer 5

Answer 6

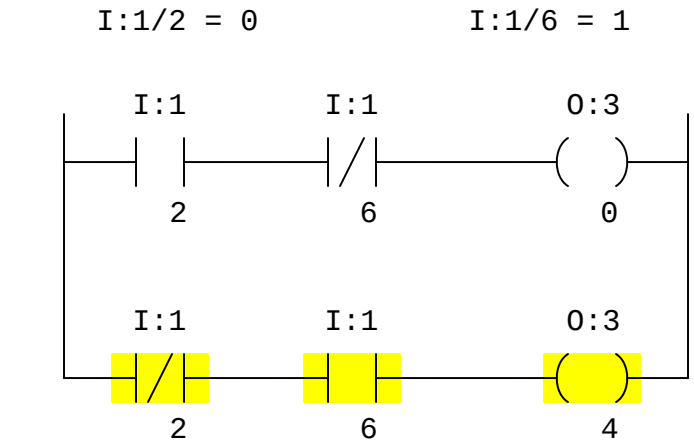
$E_{line} = 7205$ V
$I_{line} = 19.81$ A
$E_{phase(source)} = 4160$ V
$I_{phase(source)} = 19.81$ A
$E_{phase(load)} = 4160$ V
$I_{phase(load)} = 19.81$ A
$P_{total} = 247.2$ kW

Answer 7

There are no answers provided here! For help, consult the "instruction set" reference manual for your PLC, which will describe in detail how each type of instruction is supposed to function in your PLC.

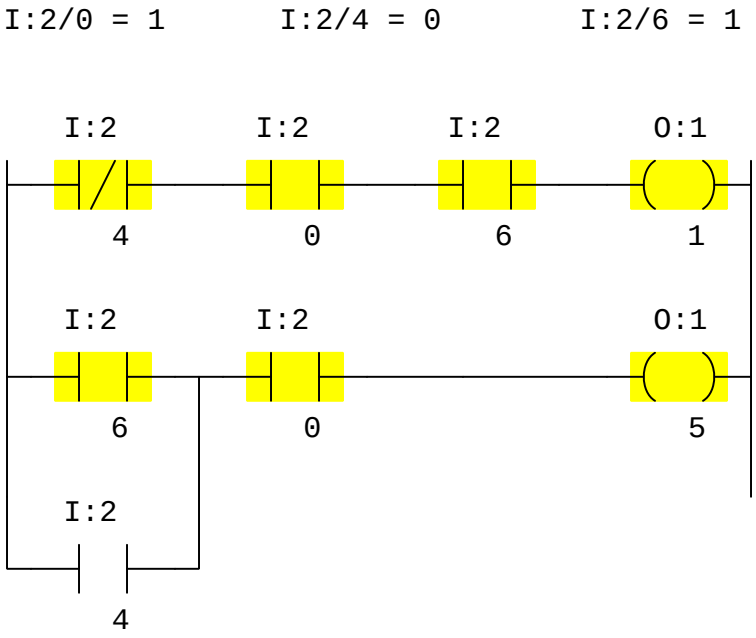
Answer 8

Output `O:3/4` will activate to energize lamp Y, but the other output (and lamp) will remain off:



Answer 9

Both the lamp and the solenoid coil will be energized:



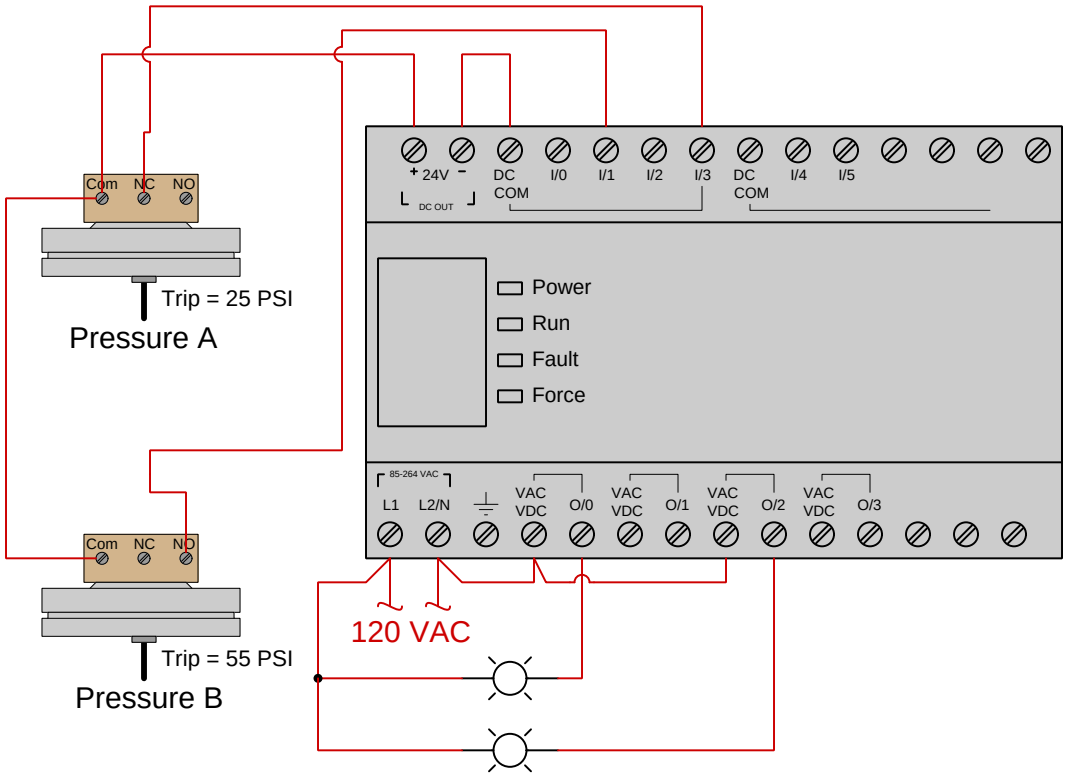
Answer 10

Color in the online program display reveals a path for "virtual power" in the ladder-logic "circuit". This means every colored "contact" is in its closed state, while every uncolored "contact" is in its open state. Since we see that only the normally-open "contact" instructions are colored while all the normally-closed "contact" instructions are uncolored, we know that all bit states must be one (1).

A "one" (1) input bit state is caused by real electrical power applied to that PLC input channel. This means both inputs must be energized by pressure switches that are *closed*.

Since pressure switch A is experiencing a pressure of only 14 PSI (below the trip threshold of 25 PSI), it must be in its resting state. Thus, we must wire its *normally-closed (NC)* contact to channel `I:0/3` of the PLC.

Since pressure switch B is experiencing a pressure of 70 PSI (above the trip threshold of 55 PSI), it must be in its actuated state. Thus, we must wire its *normally-open (NO)* contact to channel `I:0/1` of the PLC.



Answer 11

Answer 12

Answer 13

Answer 14

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

Pressure "A" is *greater than* 25 PSI. Pressure "B" is *greater than* 55 PSI. Both inputs are *sinking* current from the switches.

Answer 23

Answer 24

Answer 25

Although starting all three conveyor motors simultaneously would be very simple, it would be a bad thing to do because of the *inrush current* of all three motors placing undue load on the power system.

Answer 26

Input switch electrical "normal" statuses:

- **Start** = NO
- **Stop** = NC
- **PSL** = NC
- **PSH** = NC
- **Reset** = NO

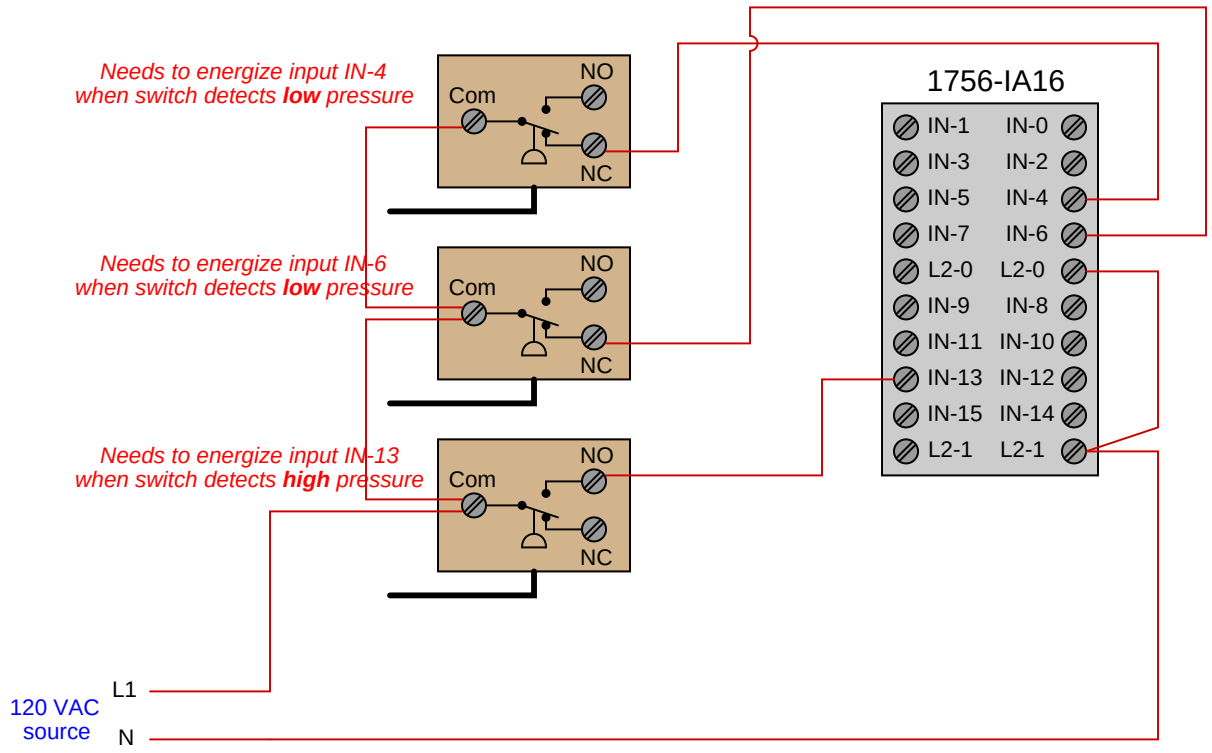
Answer 27

Partial answer:

$E_{line} = 277$ V
$I_{line} = 0.133$ A
$I_{phase(load)} = 0.133$ A

Answer 28

Answer 29



Answer 30

The purpose of the parallel-connected 14.3 kΩ resistor is to provide a path for current to each connected channel of the input card even when the discrete switch is in the open state. The card has *two* optocoupling devices per channel: one for detecting this "leakage" current and another for detecting the full-on current when the switch closes. Thus, the card has the ability to monitor wiring continuity even when the field switch device is in the "off" state.

The leakage current range necessary for diagnostic monitoring of input wiring is between 1.2 mA and 1.5 mA inclusive. In order for the card to detect a full-on condition, the current must lie within the range of 2 mA (10 VDC) to 13 mA (30 VDC).

Answer 31

Necessary conditions to start the pump:

- Pressure must be less than 20 PSI for at least 17 seconds
- Selector switch must be in the "left" position
- Pushbutton must be released (unpressed) **or** level more than 3 feet

Answer 32

The liquid level must exceed 5 feet in height for at least 25 seconds **and** the selector switch must be in the "right" position in order for the pump to turn on.

Answer 33

The oil pump will start up when the "Start" pushbutton is pressed. It will "seal in" and latch when the oil pressure has reached its minimum value, necessitating the operator hold the "Start" button pressed for some minimum amount of time during the start-up procedure.

The blower delays turning on for 15 seconds, this time delay set by timer `T4:0`. A solenoid-operated air valve actuates simultaneously with the blower motor.

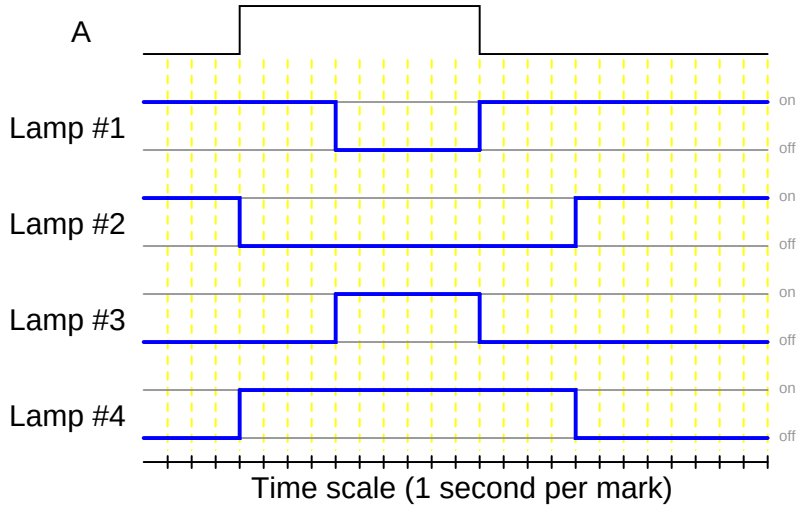
If the "Run/Stop" switch is set to the "Stop" position, the blower and solenoid valve de-energize, but the oil pump continues to run for 15 seconds (post-lube) controlled by timer `T4:1`.

If any of the emergency shutdown permissives are lost (any of the colored contacts in rung 0), both the blower and the oil pump shut off immediately, and the solenoid-operated valve also returns to its de-energized position.

Shutdown conditions:

- Emergency stop pushbutton
- Low oil pressure
- Low oil level
- High pump vibration
- High fan vibration
- High temperature

Answer 34



Each contact with an arrowhead pointed *toward* the energized position is an **on-delay** contact, whereas each contact with an arrowhead pointed *away* from the energized position (i.e. toward the "normal" state) is an **off-delay** contact.

Time-delay relays are not the easiest for some students to understand. The purpose of this question is to introduce students to the four basic types of time-delay relay contacts and their respective behaviors. Discuss with your students how the contact symbols make sense (arrows on the switch actuators describing direction of delay).

Note to your students how it is possible to have different types of time-delay contacts actuated by the same relay coil.

Answer 35

Answer 36

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

This is a graded question – no answers or hints given!

Answer 42

This is a graded question – no answers or hints given!

Answer 43

This is a graded question – no answers or hints given!

Answer 44

This is a graded question – no answers or hints given!

Answer 45

This is a graded question – no answers or hints given!

Answer 46

This is a graded question – no answers or hints given!

Answer 47

This is a graded question – no answers or hints given!

Answer 48

This is a graded question – no answers or hints given!

Answer 49

This is a graded question – no answers or hints given!

Answer 50

This is a graded question – no answers or hints given!

Answer 51

Answer 52

Your loop diagram will be validated when the instructor inspects the loop with you and the rest of your team.